TRANSITION PATHWAYS TO SUSTAINABLE ENERGY INFRASTRUCTURE: THE UK EXPERIENCE

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Dedication

This thesis is dedicated with love to my parents

For their priceless heritage of education, integrity and love.

Acknowledgements

This thesis is the result of four years of painstaking research activity at the Civil Engineering Department in the school of Computing, Science, and Engineering (College of Science and Technology) of the University of Salford, Manchester. I greatly appreciate all who have contributed directly or indirectly to the content of the thesis, to the underlying work, and to my personal life during this period.

First and foremost, I express my profound gratitude to Almighty Allah for His overall guidance. Also my gratitude goes to my supervisor, Prof. Miklas Scholz, for his relentless and fruitful support and participation throughout the four year period, even in the most challenging times. The creative input, optimism, and trust and all other remarkable opportunities created have enabled me to excel during the last four years. Furthermore, I would like to acknowledge the valuable contribution of my co-supervisor, Asa Hedmark who has proved effective in shaping this thesis as well as myself as a person.

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I am immensely grateful for all my family members, my parents (Hussaini Mohammed and Fatima Mustapha), brothers (especially, Mustapha, Abba and Ali) and sisters who have always provided a solid foundation for everything. A huge thank is due to my lovely wife Hafsat Usman Mohammed, who helped in easing my life in all its ramifications in the process of this achievement. She lifted many necessary activities who could have been a burden, and hence hindrance to a smooth progress of this work. I would like to specifically acknowledge the grass roots input of my late father, Alhaji Hussaini Mohammed, who has laid the solid and main foundation to this uppermost achievement, but sadly didn't live long enough to witness it. I treasure you all for sharing the most precious times and resources in helping me to find a balanced life, and just for who you are.

Finally, I sincerely hope that this thesis will be a step towards a sustainable energy infrastructure and a cleaner global environment that is habitable to future generations.

Declaration

I declare that this thesis is a presentation of my original research work. Wherever contributions of others are involved, every effort is made to indicate this clearly. This study has not been previously submitted for a degree or a similar award at any institution. The work was done under the supervision of Professor Miklas Scholz, at the University of Salford, Manchester, United Kingdom.

Contents

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Abbreviations and Symbols

BEV	Battery Electric Vehicle
CCC	Committee on Climate Change
CCGT	Combined Cycle Gas Turbine
CDM	Clean Development Mechanism
CER	Certified Emissions Reduction
CMP	Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol
CO2	Carbon dioxide
COP	Conference of the Parties
CTL/GTL/BTL	Coal to Liquids/Gas to Liquids/Biomass to Liquids
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DfT	Department for Transport
EE	Energy efficiency
EEA	European Environment Agency
EEB	European Environmental Bureau
EI	Emissions Intensity
EPWR	European Pressured Water Reactor
ES	Emissions Saving
ETS	Emissions Trading Scheme
EU	European Union
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FCV	Fuel Cell Vehicle
GDP	Gross Domestic Product
GEF	Global Environment Facility
GHG	Greenhouse Gas
GMT	Global Mean Temperature
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine

ICEV	Internal Combustion Engine Vehicles
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land-Use Change and Forestry
MLP	Multi-level Perspective
MPP	Multi-phase perspective
NAEI	National atmospheric emissions inventory
NGO	Non-Governmental Organisation
NOx	Nitrous oxides
NT	Niche Technology
NWRS	National Wildlife Refuge System
O3	Ozone
PC	Performance-cost
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate matter
PPM	Parts Per Million
PPP	Purchasing Power Parity
R&D	Research & Development
RT	Regime Technology
SEPA	Scottish Environment Protection Agency
SMMT	Society of Motor Manufacturers and Traders
SO2	Sulphur dioxide
UK	United Kingdom
UKERC	United Kingdom Energy Research Centre
ULCV	Ultra Low Carbon Vehicle
ULEV	Ultra Low Emission Vehicle
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USEPA	United States Environmental Protection Agency
VOC	Volatile Organic Compounds

Units

$05p	GDP at constant 2005 prices in US Dollars
co2eq	Carbondioxide equivalent
g	Gram
h	Hour
hh	Household
k	Kilo/Kilogramme
km	Kilometer
koe	Kilogram of oil equivalent
kt	Kilotonne
ktoe	Kilotonne of oil equivalent
m	Mega
MWh	Megawatt hour
mt	Megaton
mtoe	Megaton of oil equivalent
t	Tonne
toe	Tonne of oil equivalent
W	Watt

List of papers submitted/presented/published

A. Paper(s) Presented & Published (2014)

1. Hussaini, M., & Scholz, M. (2014). Socio-technical transition of Coal-CCGT in the UK Electricity Sector. *IAFOR 2014: The international academic forum conference, NACSEE.* September 11-14, 2014, Providence, Rhode Island, United States.

B. Paper(s) presented (2015)

1. Hussaini, M., & Scholz, M. Assessing the roles of the various socio-technical transition pathways in low carbon transition in the UK. *ICCE 2015: International Conference & Exhibition on Clean Energy.* September 14-16, 2015, Ottawa, Canada.

C. Paper(s) submitted to journals for publication (2014/2015)

1. Hussaini, M., & Scholz, M. Alternate sequence of transition pathways. *Journal of Energy for Sustainable Development.* (submitted).
2. Hussaini, M., & Scholz, M. Using numerical approach to study sustainability transitions: the case of electricity generation sector in the United Kingdom. *Journal of the Energy Institute.*

D. Paper(s) to be submitted to journals

1. Hussaini, M., & Scholz, M. A simplified typology of system transition literature.
2. Hussaini, M., & Scholz, M. Exploring low carbon transition pathways in the United Kingdom road transport sector.

Abstract

Environmental problems such as climate change resulting from greenhouse gas emissions present alarming challenge to carbon intensive energy systems. In response, the European Union at the regional level and the United Kingdom at the national level responded to this development by formulating and implementing proactive low carbon transition policies over the past few decades. Using recent transition theories, this thesis provides explorative analysis of low carbon transition pathways that have taken place and that are likely to take place, in the UK road transport and electricity generation sectors. Using reliable data and information, this research applied the concepts of transition pathway theory (the multi-level and multi-phase perspectives) in the context of energy system (as a socio-technical system) to analyse low carbon energy transition prospects in the two case study sectors. Findings indicate that transition in the road transport sector is currently at the take-off phase of transformation pathway to biofuel blends, hybrid electric vehicles, as well as niche technologies such as battery electric vehicles. For the emergence of an ideal low carbon road system in the UK, it is shown that the transformation pathway is insufficient and the likely pathway sequence to full decarbonisation will be transformation-substitution-de-alignment/re-alignment. On the other hand, the fossil fuel electricity generation sector is currently at the take-off phase of substitution pathway to renewable electricity. For the emergence of a single power generation technology, the result shows that the most likely scenario is the de-alignment/re-alignment pathway. Under this pathway, the power industry will be characterised by loosely coupled grid islands located close to consumers, necessitating bidirectional flows of electricity to balance demand and supply. At the national level, the transition assessment indicates that the overall carbon performance of the UK energy system is successful and is in agreement with the targets set in the Kyoto Protocol.

CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Greenhouse gas emissions and the environment

Greenhouse gases (GHGs) retain heat provided to us by the sun in a process known as the greenhouse effect (United States Environmental Protection Agency [USEPA], 2015). It occurs naturally and without them, the planet (earth) will be too cold to sustain life. Since the beginning of industrial revolution in the mid-1700s, the levels of carbon dioxide – a powerful GHG have risen by 35% largely from the burning of fossil fuels such as coal, oil and natural gas (Murphy & Hsu, 2008). With more emission of GHGs, the atmosphere acts like a thickening blanket and traps more heat, thereby enhancing the natural greenhouse effect and on average resulting into an additional warming of the Earth's surface and atmosphere. Subsequently, this increase in the earth's temperature gives rise to a climate change phenomenon known as Global Warming which could have adverse effect on natural ecosystems and humankind.

The fact that global warming caused by anthropogenic GHG emissions such as carbon dioxide, methane, nitrous oxide, ozone and synthetic chemicals is already taking place and is a problem caused by human activities is firmly established by an increasing number of scientific sources, amongst them the Inter-governmental Panel on Climate Change (IPCC). Failure to tackle global warming could have dramatic consequences; rising sea level with shrinking glaciers, an increased frequency in droughts, floods and tropical storms will put half of the world's species at the risk of extinction and hundreds of millions of people in desperate need of food and water. Scientists estimate that further warming above 3 degrees Celsius is likely to decrease global agricultural potential. Storms are also expected to be more frequent and intense in a warmer world. Water will rapidly evaporate from the soil, causing it to dry out faster between rains. Droughts are projected to become longer and more intense. This has already been observed since 1970s in the tropics and subtropics (Intergovernmental Panel on Climate Change [IPCC], 2007a, 2007b).

To have a reasonable chance of avoiding such dire consequences, the global average temperature must not increase by more than 2 degrees Celsius above the pre-industrial level. According to the IPCC, this necessitates an overall 50 to 85% reduction in global GHG emission from 2000 to 2050. The good news is that it is possible to reduce global warming by 85% by 2050. Alternative to fossil energy which currently accounts for 80% of the world's energy use and which is responsible for 60% of global GHG emission is one practical solution. Solar, wind power and hydrogen fuel cells that emit no GHGs are low pollution alternatives to fossil fuel. Other alternatives include fuel made from plants such as biodiesel and ethanol. Use of these fuels can reduce total carbon dioxide emission from the atmosphere. This necessitates a significant shift in the historic pattern of fossil-fuel use and a major transformation of the global energy system (Committee on Climate Change [CCC], n.d.a; International Energy Agency [IEA], 2013; United Nations Framework Convention on Climate Change [UNFCCC], 2014a).

1.2 GHG emissions reduction commitment

The UNFCCC sets the overall framework for intergovernmental efforts to tackle the challenge posed by global warming. The ultimate objective of the convention is to achieve stabilisation of GHG concentrations in the atmosphere at a level that would prevent dangerous atmospheric interference with the climate system. To enhance the level of participation in emissions reduction, particularly among developed countries, the convention came up with an international agreement (a protocol) adopted on the third conference of parties (COP 3) in Kyoto, Japan, on 11 December 1997 known as the Kyoto Protocol, that sets binding targets for Annex I parties (Appendix A) to achieve strategic emissions reduction figures through high level commitment. The convention on climate change also recognises the importance of providing developing countries with finance, technology and capacity building support to mitigate and adapt to the impacts of climate change. The principal difference between the convention and the protocol is that while the former encourages countries to stabilise and reduce their emissions, the later commits them to do so (United Nations, 1992; UNFCCC, 2014d).

The Kyoto protocol sets binding targets for Annex I countries and programmes and activities for developing countries (Appendix A). The Protocol establishes three flexible mechanisms that can be used by parties with GHG reduction commitment to achieve the objectives of the convention in a cost-effective way (UNFCCC, 2007).

These are:

1) International Emissions Trading (IET); Countries with commitments under the Kyoto Protocol can acquire emission permits from other countries with commitments under the Protocol and use them towards meeting a part of their targets.

2) Clean Development Mechanism (CDM); The CDM allows a country with an emission reduction commitment under the Kyoto Protocol to earn certified emission reduction (CER) credits, by taking part in emission reduction (or emission removal) projects in developing countries. The resulting CER credits (each equivalent to one tonne of CO2) is counted towards meeting its Kyoto target.

3) Joint Implementation (JI); This mechanism allows a country with an emission reduction commitment under the Kyoto Protocol to earn emission reduction units (ERUs), by taking part in emission reduction (or emission removal) projects in any other country with a

commitment under the Protocol. The resulting ERU (each equivalent to one tonne of CO_2) is counted towards meeting its Kyoto target.

The Kyoto Protocol is seen as an important first step towards a truly global emission reduction regime that will stabilise GHG emissions, and can provide a plan for the future international agreement on climate change.

1.3 The challenge of low carbon energy transition

The increasing consequence of GHG emission (which is believed to significantly contribute to global warming more than ever before) and the resulting need to reduce carbon dioxide (CO_2) impact by target setting is clearly acknowledged by many governments (A. Smith, 2010). A principal requirement is that a large-scale reduction in carbon dioxide emissions (especially from industrialised countries) will be necessary sometime in the second half of this century (UNFCCC, 2007). According to the IPCC, developed countries as a group should reduce their GHG emissions to below 1990 levels by 25 to 40 per cent by 2020 and by 80 to 95 per cent by 2050 through domestic and complementary international efforts, while developing countries as a group should achieve a substantial deviation below the currently predicted rate of growth in their emissions, in the order of 15 to 30 per cent by 2020 (UNFCCC, 2014a). This requirement can only be realised by deep structural changes in the emitting industry sectors, in particular the power sector which is the largest CO_2 emitter, contributes 26% (above one-quarter) of global CO_2 emissions (Wheeler & Ummel, 2008) and can be a driver to a greener economy. This underpins recent interest on new investment in low carbon energy infrastructure.

However, for transition to a sustainable low carbon economy, experts argue that as a main functional requirement, the energy infrastructures (which are crucial to modern industrial societies) must be sustainable (Rotmans et al., 2000, cited in Chappin & Dijkema, 2008b). In recent years, this has led to an increasing interest in both energy transitions and energy-related system innovation in order to achieve advances in environmental efficiency. The task of decarbonisation is a holistic transition from one set of inter-related socio-technical elements to an alternative low-carbon set that meets equivalent (or the same) social functions (Shackley & Green, 2007). According to Foxon (2011), transitions in energy systems involves changes to practices of energy use; innovation and deployment of a range of low carbon technologies, a broader change in the energy mix of industries within national and global economies. Basically, system transitions in energy will require revolutionary changes to systems providing energy and other services for domestic and industrial purposes. As emissions regulations tighten, scientists focus more attention on the role of several transition theories in the field of energy transitions. Transition theories provide important combination of concepts and ideas and have been used in the historical analysis of technological change such as transitions from horse-drawn carriages to automobiles, from sailing ships to steam ships (Shackley & Green, 2007).

However, the descriptive body of knowledge on transition (Chappin & Dijkema, 2008a) implies that it is impossible to know what the future system of energy supply and demand will look like, how fast such a transition might occur or how it may be brought about. In addition, the inherent complexity of energy infrastructure (Chappin & Dijkema, 2008b) implies that providing adequate explanation for their transitions requires the proper understanding and recognition of the social components (humans, governments & businesses) and the technical components (physical technologies) as well as the interplay or interaction (communication, ownership and material flows) between them (Mitchell and Newman, 2002). In more clear terms, these are the actors (energy providers/institutions), regulators (government) and technologies (technical components or physical technologies) and of the socio-technical design space. The design space for energy systems includes technological structure and content, policy, regulation and market design and social innovation. This necessitates domain knowledge, within a multi-level (micro-meso-macro) framework, that shape infrastructure and industry innovation, evolution and transition towards a sustainable energy system.

Moreover, energy transitions take time because energy infrastructures exhibit only gradual and limited improvements of system performance with respect to CO2 emission (Rhodes, 2007; Chappin & Dijkema, 2008b). The relatively short timescale of the necessary transition to a low carbon economy is therefore likely to prove challenging (Kessides & Wade, 2010). For instance, there are fears that a very rapid transition to a renewable-energy economy could lead to the ingestion of energy from existing power plants and thus jeopardize energy security. In fact, major innovations in the past having taken decades to diffuse and even longer to have the supporting infrastructures developed (Pearce, 2008, 2009; Kenny, Law, & Pearce, 2010). It is important to note that even in the Netherlands case, observers argue that the rapid transition of six-year timeframe from coal to oil and gas as major sources of energy was in reality, the acceleration phase of the transition. The preparation for this breakthrough, the so-called pre-development phase, was considerably longer (Rotmans, Kemp, & van Asselt, 2001). Considering the complexity of today's energy infrastructure, it is a huge challenge to reinvent and re-design this socio-technical system, let alone develop a program suitable for managing its transition (Herder et al., 2008). The challenge is that apart from the scientific uncertainty over the extent and severity of manmade climate change, unseen forces may derail efforts towards large-scale decarbonisation. However, energy and environment experts have come to accept the scientific argument for a significant reduction of energy system emissions which implies a change of technology (Shackley & Green, 2007).

1.4 Current approach and originalities on transition pathway literature

Currently, there is a growing body of literature on the concepts of socio-technical transitions towards sustainability. The challenge of transition concepts is that despite all the prevailing knowledge and research efforts on how they come about, to capture their dynamics in real world is not trivial. Two basic approaches are to use the concepts of multi-level and multi-phase perspectives (MLP and MPP) for the analysis of transitions to conceive how they come about in order to enable transition management. The MLP indicates that transitions result from the interplay of dynamics among multiple levels involving different transition pathways, whereas the MPP shows that transitions are non-linear involving different phases (Geels, 2006a; Loorbach & Rotmans, 2006; Rotmans et. al., 2001). The MLP is used to explain ways through which configurations of technologies, infrastructures, policy, social practices, institutions and markets can change to meet their functions in a more sustainable way. It is developed to describe and analyse these complex, long-term processes. Its applications include analysing historical and ongoing transitions, envisaging future transitions and guiding policy design (Geels, 2005c; Kern, 2011).

While maintaining its applications, this research work tends to use the functionality of the MLP in a novel way. Geels and Schot (2007) indicated that a possible sequence exists among the four main transition pathways (Transformation T, Reconfiguration R, Substitution S and De-alignment/Re-alignment D/R) which is either T-R-S-D/R or T-R -D/R-S depending on the magnitudes of landscape pressure and maturity of niche technologies beyond R. This research dwelled on this idea and elaborated the concept using graphical illustrations. A graph of landscape pressure against niche technology development has been plotted and the various transition pathways appropriately located while revealing their possible sequence. Analysis based on this concept shows that factors controlling the pathway sequence are very complex and are dependent upon the pathway history of a transition and government policy. This approach brings to light the hidden uncertainties about the direction of societal transitions and structural settings and hence, influence policy design.

For the MLP concept, there are no existing numerical value judgements for the three analytic levels of the framework. Therefore, the second originality in this work is that it tends to develop numerical measurements for the three levels of the MLP framework. These measurements are based on concentrations of harmful atmospheric gases for the landscape level, percent technology use for regime level and techno-economic and sustainability performance of alternative technologies for technological niche level. These numerical figures provide indications on the occurrence of the various transition phases in analysing transition processes. This work is the first to adopt a numerical approach of the multi-level perspective in the analysis of low carbon transitions pathways. The numerical approach projects in a graphical form, the possible future transition pathways, their timing and how these could affect socio-economic and infrastructural settings. This finding helps to capture transitions and transition pathways along their pathways, thus it may be said that this work has contributed new insights to the body-of-knowledge systems transitions.

1.5 Energy Infrastructure

Infrastructure is basic physical and organisational structures essential for the operation of a society or enterprise (Oxford Dictionaries, 2015). They are the physical assets and services vital for an economy to function (Sullivan, Steven, & Sheffrin, 2003). In modern industrial societies, these technical structures include facilities such as roads, transport, water supply, sewers, electrical grids, telecommunications, bridges, schools, and ports. These physical components of interrelated systems exist in the form of network of assets providing commodities and services essential to enable, sustain, or enhance societal living conditions (Chambers, 2007; Fulmer, 2009; Weisdorf, 2007). In general terms, infrastructure can be defined as the set of interconnected structural elements that provide the framework supporting an entire structure of development (American Society of Civil Engineers, 2009; Oyedele, 2012). It encompasses all basic inputs into and requirements for the proper functioning of the economy. This implies that the term infrastructure is not limited to the network of physical components that support a society, but also includes social elements like companies, governments and individuals. Also included are all the institutions required to maintain the economic, health, and cultural and social standards of a society (such as the system of government, law enforcement, regulation, standards and markets) which emerge parallel to the physical assets.

Thus infrastructure systems include both the fixed assets, and the control systems required to operate, manage and monitor the systems. The system is multi-domain, multi-actor and multi-level and is affected by all sorts of actor decisions and actions; each with its own interest, means and preferences (Chappin, 2011). The individual technological elements in these infrastructures are therefore, the technical component of the system. Infrastructure may be classified into economic infrastructure such as utilities, airports, pipelines, power stations and social infrastructure such as healthcare facilities, education facilities and correctional facilities (Hsu & Newell, 2007). Another classification is based on the purposes for which infrastructure is intended and includes energy infrastructure, transportation infrastructure, water management infrastructure, communications infrastructure (Luger, Butler, & Winch, 2013; The Institution of Engineering and Technology, 2011). Similarly, energy infrastructure may be summarised under the following highlights:

- The physical infrastructure required for the exploration, development and production of energy;
- Transformation of energy, such as electric power generation and oil refining;

- Transmission and distribution of energy, such as electric power transmission lines and oil and gas pipelines;
- Storage of energy products.

Therefore, energy infrastructure system may refer to all social and technical components that are involved in producing, processing, transporting and use of energy products and services for societal functions. Energy infrastructures therefore include not only technical facilities like power plants, refineries, electric grids, oil and gas pipelines etc. but also inclusive is the social elements like institutions that manage these facilities (Chappin, 2011). Figure 1.1 below shows the various technical and social components of the system and how they are related.

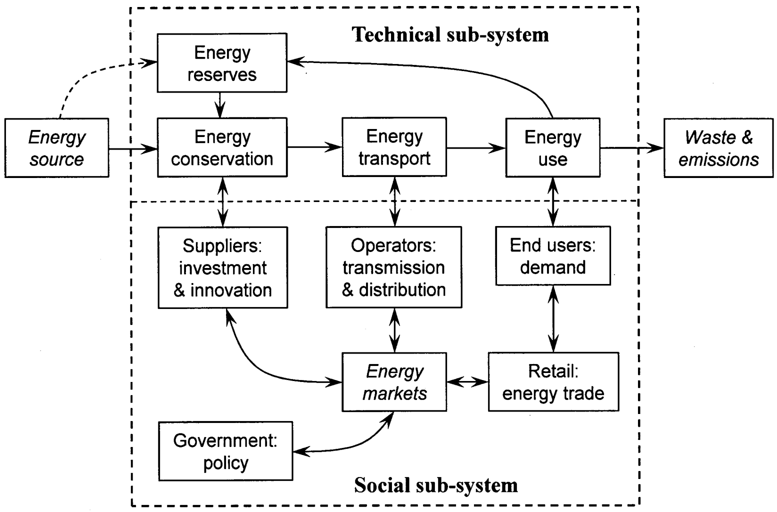


Figure 1.1. Socio-technical network of energy infrastructure (Chappin, 2011)

1.5.1 Energy infrastructure as a complex socio-technical system

It can be seen from Figure 1.1 that energy infrastructure system is a combination of social and physical subsystems that exist and operate in an interactive network, forming a complex socio-technical system (Hughes, 1987; Ottens et al., 2006). In general terms, socio-technical system may be defined as a set of interconnected social and technical elements that provide framework supporting an entire structure of development. Domains in the technical (technology) and social (institutional and economic) subsystems are strongly interdependent. This definition suggests that it may be difficult if not impossible to separate activities in social and technological elements. The system is also influenced by an external environment in which it is embedded. The environment influences system behaviour as it is being influenced by the system as well; it is a two-way effect (Houwing, Heijnen, & Bouwmans, 2006). In other words, the subsystems interact with one another and with the external environment, connecting the supply and demand sides of the economy.

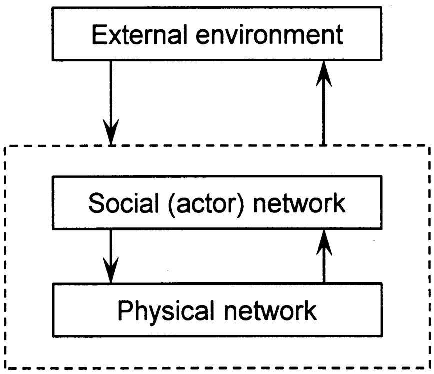


Figure 1.2. Interactive framework of socio-technical system (Houwing et al., 2006)

Thus, understanding socio-technical (infrastructure) system entails understanding the order of relations between the technical elements, between the social elements, between the social and technical (system) elements and also between the system and the external environment. The complexity in energy infrastructure means that it contains a large number of elements that interact in a complex way.

1.5.2 Socio-technical transition of energy infrastructure

It is important to note that an underlying criterion in energy transitions is to acknowledge the complexity in energy infrastructure. One crucial feature of complex systems theory is that components in a system are complex themselves, giving a hierarchy of levels in which the components interact (Simon, 1973). Higher levels are more stable and slower changing whereas lower levels are less stable and faster changing (Holling, 2001). The system elements are characterised by micro-diversity in behaviour; individual behaviour at the micro level is relevant to the system behaviour at the macro level and thus, the evolution of the system is a result of the outcome of its discrete elements behaviour (Van Geenhuizen et al., 2010). The energy system consists of all activities of energy production, supply, markets and consumption, combining both the technical and social components and networks that are strongly interdependent (Houwing et al., 2006).

> The energy infrastructure is clearly a λ-system: actors have been liberalised and competitive tasks (power and natural gas generation and retail services) were unbundled from monopolistic tasks (grid and pipeline operators); the sector is embedded in and strongly connected to several markets, i.e. fuel, emission-trading and spot markets. All the actors active in these markets have their own objectives to realise their objectives and means to do so. And the government has to set the rules of the game, with policy and regulation as main instruments, in such a way that actors by realizing their goals will have optimum behaviour according to the policy makers set of objectives (Chappin & Dijkema, 2009, pp. 5-6).

Therefore, the energy system is a typical (large-scale socio-technical, λ) complex system. The socio-technical approach to low carbon transitions conceptualises energy infrastructure as a composition of social and technical elements such as technology, policy, science, culture, markets and consumer practices (Geels, 2004). Actors and special interest groups include policy makers, companies/industries, civil society, consumers, engineers and researchers (Geels, 2012). The transition process is a co-evolutionary one and a collective shift in these elements is termed socio-technical transition (Geels, 2005a; Geels, 2006a).

1.6 Scope of thesis

The thesis exhaustively covered literature on transition pathway theory and the transition prospects of road transport and electricity generation sectors in the UK. The multi and interdisciplinary approach combines insights from engineering, energy policy, economics and social sciences. This is built around the UK's ambition of a large-scale reduction of carbon dioxide emissions of 80% sometime in the second half of the 21st century (CCC, n.d.a). To understand the dynamics of energy transitions, the thesis introduces a socio-technical system approach which involves all the relevant components in the energy system to assess the transition of the case-study sectors. The combination and interrelation of transition pathway theory, complex system theory and energy infrastructure system shall be identified in this thesis. Figure 1.3 below shows a flow chart of the thesis content.

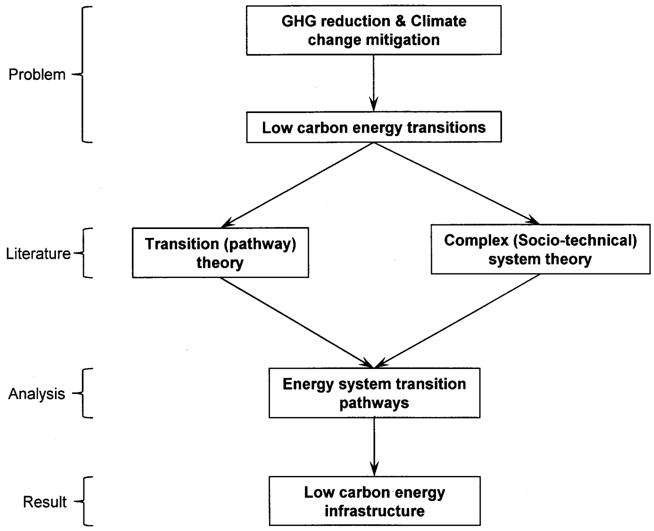


Figure 1.3. Scope of the thesis

The problem part of the figure indicates that there is the need to cut GHG emissions which are the main cause of climate change and global warming. This can only be achieved through a transition of carbon intensive energy infrastructure to a low carbon alternative. The literature deals with theories on transition pathways of complex socio-technical systems. The analysis involves both theoretical and numerical approaches to determining the transition state of the two case study energy sectors (road transport and power generation) in the UK. The result is indicative of the end-state of the transition.

1.7 Aims, objectives and contributions of the research

The overall aims of this thesis are centered on two main objects as follows:

1) To contribute to theoretical knowledge on describing potential transition scenarios in terms of emerging technologies that is useful in informing policy-makers and other stakeholders in the UK energy system. This is necessary to enable them understand how social and political issues (such as public acceptability of technologies and institutional changes, the kind and setting of policies and their paradigm), interact or co-evolve with present and expected future changes in technologies.

2) To provide a clear description of the two main concepts of transition pathways, i.e. the multi-level and multi-phase perspectives and apply their functionality in the analysis of current and future low carbon transitions pathways in the UK at current transition dynamics. This helps to identify bottlenecks in the UK's low carbon transitions.

The objectives are:

- To select suitable energy consuming and carbon emitting sectors in the UK for case study (road transport and electricity generation);

- To adopt a theoretical approach to the MLP and MPP concepts to analyse the UK's low carbon development progress in road transport sector in terms of transition pathways;

- To adopt a numerical approach to the MLP and MPP concepts to analyse the UK's low carbon development progress in electricity generation sector in terms of transition pathways;
- To study the technical, social and economic impact of the various pathway scenarios.

Thus, the research helps to determine alternative plausible governance patterns for road transport and electricity generation infrastructure in the UK and how they could affect technological, institutional and social changes in these systems.

1.8 Audience and perceived Benefits

The strategic decision makers in energy infrastructures are the problem owners. Regional, national, and international governments make decisions on energy policy (Appendix B). Energy companies, energy infrastructure providers, technology providers, and energy users make their own decisions and are (to some extent) affected by the decisions of governments. They are, therefore, part of the audience of this thesis. The thesis is relevant for complex systems researchers, and more specifically, for transition managers. The overall benefit of this research work is that it supports efforts towards reducing GHG emission levels in the energy domain in the most cost effective manner. The work focuses on evaluating existing transition progress and recommends new steps as appropriate.

1.9 Structure of report

The thesis is structured as follows; Chapter 1 introduces the subject matter, reflecting on key areas of discussion. Chapter 2 provides details on literature concerning transition and transition pathways theory. This includes literature on system transition and conceptualisation of the emergence of transitions. Chapter 3 outlines the methodological approach of the thesis. This includes the use of the MLP and MPP concepts in the analysis, selection of case study sectors as well as methodology on data collection. Chapter 4 provides detailed analysis on the characteristics and sequential behaviour of transition pathways. This is derived from the principle of the multi-level perspective framework. Chapter 5 used the theoretical concepts of the multi-level and multi-phase perspective to analyse the transition prospect of the UK in road transport sector. Similarly, Chapter 6 used numerical concepts of the multi-level and multi-phase perspective to analyse the transition prospect of the UK in electricity generation sector. For the electricity sector, numerical values are established for measuring the transition impacts of the three levels of the MLP. A transition momentum derived from these values and is used to forecast present and future pathways. Chapter 7 assess the overall low carbon transition progress in the UK. Chapter 8 draws conclusions on the state of UK's road and power infrastructure in terms of low carbon energy transition and provides recommendations on how best to manage and achieve a successful and cost effective transition.

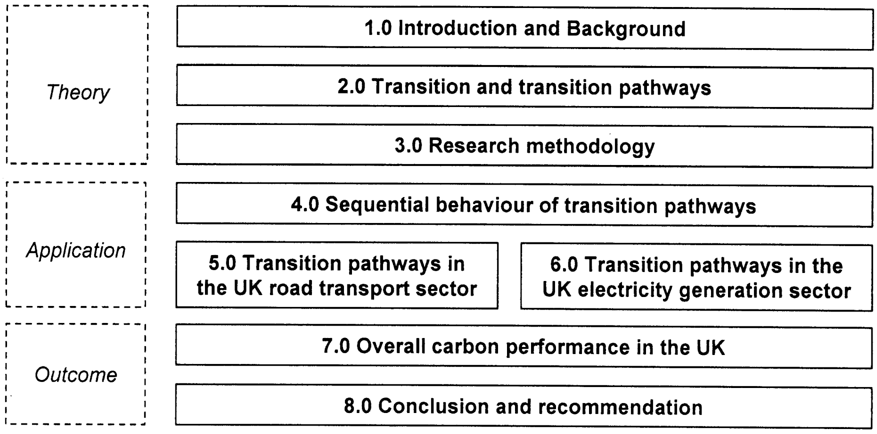


Figure 1.4. Structure of the thesis

In this thesis, three interdependent parts can be distinguished (Figure 1.4):

- A theoretical part or the lead-in which forms the input and elaborates on transitions theory/literature and methodology (chapters 1, 2, & 3);
- The application part or the core (chapters 4, 5 & 6) which entails the main activities of the thesis; and
- The outcome or lead-out (chapters 7 & 8) where observations, conclusions and recommendations have been provided.

CHAPTER 2

TRANSITION AND TRANSITION PATHWAYS

2.1 Introduction

The concepts of transition have been introduced in the field of energy to study its sustainability to solve the problem of climate change. Generally, transition is the process or a period of changing from one state or condition to another. Transition concept is a proactive, positive visioning, forward thinking approach to the realities of future. The transition framework offers analytical tools for structuring and explaining the complexity and dynamics of societal systems such as energy infrastructure. This chapter focuses on the professional literature on system transition with emphasis on transition pathways.

2.2 Meaning of Transition

Transitions are long-term transformation processes (usually 25-50 years) in which society changes in a fundamental way over decades or generations (Rotmans & Kemp, 2003). They are a result of a co-evolution of technological, institutional, cultural, ecological and economic developments on various scale levels (Rotmans et al., 2000, cited in Van der Brugge, Rotmans, & Loorbach, 2005). Rotmans et al. (2001) defines a transition as 'a gradual, continuous process of change where the structural character of a society (or a complex sub-system of society) transforms.' Complex societal (sub-) systems include energy supply, mobility, housing, agriculture, health care, and so on. On the other hand, societal transitions are defined as structural innovations of societal systems in reaction to issues threatening development or continuity of existing systems (Rotmans, 2005; Rotmans et al., 2001; Van der Brugge et al., 2005; Timmermans, 2006). These issues are entrenched throughout large parts of society. In other words, transitions come about when the dominant structures in society (regimes) are put under pressure by external changes in society, as well as endogenous innovation (Loorbach, 2010). The general notion is that transitions result to important fundamental changes in functional societal systems.

Transitions are a result of the interplay of multi-level developments in different domains; this implies that they are multi-dimensional with different dynamic layers. For a transition to occur, several developments must come together in several domains for a transition to occur. This causes a path of development based on new practices, knowledge, social organisation and different guiding principles. In other words, a transition can be described as a set of connected changes, which reinforce each other but take place in several different areas, such as technology, the economy, institutions, behaviour, culture, ecology and belief systems. They emerge over time as fundamental change of large-scale socio-technical systems. The goals of a transition are ultimately chosen by society, but governments can play a role in bringing about structural change in a gradual manner. Although government policy can influence the direction, scale and speed of development paths, it will never assume entire control over them. Transitions involve a range of possible development paths and they are not uniform, and nor is the transition process deterministic: there are large differences in the scale of change and the period over which it occurs (Chappin & Dijkema, 2009; Rotmans et. al., 2001).

Therefore, the management of transitions will involve sensitivity to existing dynamics and regular adjustment of goals to overcome the conflict between long-term ambition and short-term concerns. Transition management can be summarised under the following characteristics (Loorbach, 2007; Rotmans et. al., 2001):

- long-term thinking for framing short-term policy;
- multi-domain, multi-actor, multi-level approach;

- Participation from and interaction between stakeholders.
- learning-by-doing and doing-by-learning;
- aligning system innovation and system improvement;
- keeping a large number of options open.

2.3 System Transition

Within a complex system, there are many different interdependent components including actors who have specific goals, objectives and means to attain, and technological subsystems with limited capabilities (Chappin & Dijkema, 2008a). Actors and special interest groups include policy makers, companies/industries, civil society, consumers, engineers and researchers (Geels, 2012) while technical elements include the physical assets. Consequently, these domains and elements may be grouped into two broad components or subsystems; the social and technical subsystems to give a socio-technical system. The socio-technical approach to transitions conceptualises a system as a composition of social and technical elements which emerge in a co-evolutionary manner (Rip & Kemp, 1998; Geels, 2005a). Therefore, socio-technical system transition can be defined as a structural change in both the technical and social subsystems of a system (Chappin & Dijkema, 2008b).

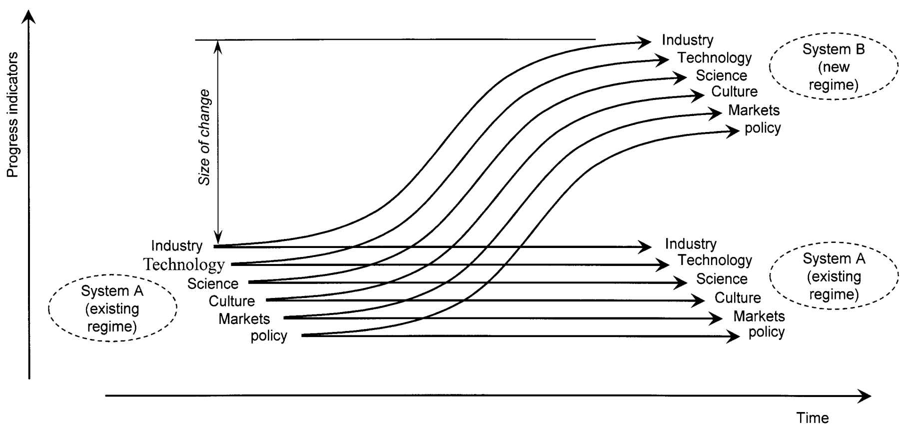


Figure 2.1. Socio-technical system with and without transition

Figure 2.1 above shows a socio-technical system with transition (system A-B) and without transition (system A-A) over a certain period of time. Therefore, transition of socio-technical system is a holistic and evolutionary change in both the technical and social components of the system. A major shift of socio-technical systems is referred to as socio-technical transitions. The scale of transition (regime change) is one important consideration in socio-technical transitions. Energy system can be viewed as a large-scale socio-technical system because it comprises heterogeneous elements like technology, policy, markets, etc. (Chappin & Dijkema, 2008a; Kemp, Schot, & Hoogma, 1998; Elzen, Geels, & Green, 2004; Geels, 2004; A. Smith, Stirling, & Berkhout, 2005; Verbong & Geels, 2007; A. Smith, 2007). Actor groups that are involved include firms and industries, policy makers and politicians, consumers, civil society, engineers and researchers. These actors initiate and bring about changes in elements in socio-technical systems.

It has been argued that it is only by structural change, system innovation of the energy infrastructure, that the long-term goals of CO_2 emission reduction can be met. If policy intends to lead to structural change in a large scale system for whatever reason, it is likely that a system transition is needed (Figure 2.2a). For the energy domain, managing a system transition implies the design of energy policy and regulation that invokes change by influencing the actions of stakeholders that in the system are in control of energy technology (Hughes et. al., 1987). A design of a system transition should lead to the optimal structural change by taking the preferred transition pathway in a large scale system as in Figure 2.3. Therefore, the policy needed for structural change is only effective when it initiates a transition to an optimal end state. In addition to requirements for the end-state, there might be requirements or objectives for the pathway of the transition itself (Figure 2.2b). Incorporating the transition pathway and end state adds a new dimension to the complexity of policy design (Chappin & Dijkema, 2008b).

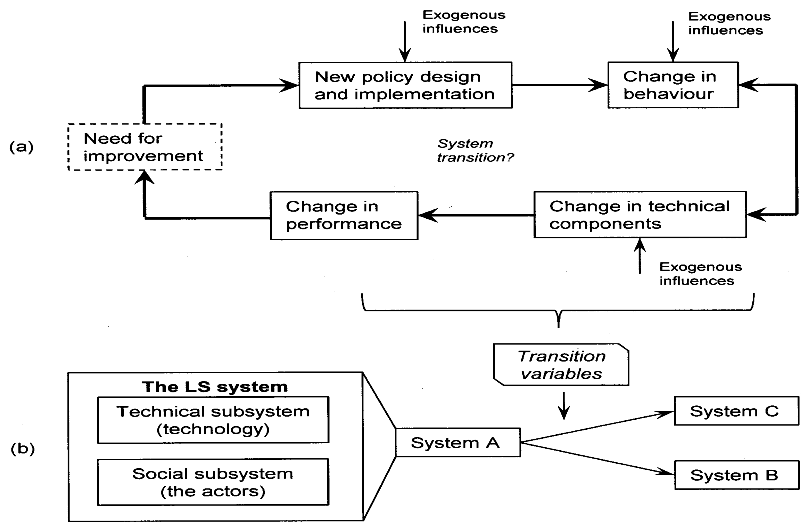


Figure 2.2. Design of a system transition (Chappin & Dijkema, 2008a, 2008b)

A system change (system transition) does not occur without a reason. It is a response to an external phenomenon, causing an imbalance in a system, thus re-adjusting itself for a new balance. In system transition design, design of the technical subsystem is augmented with policy and regulation to give an all-inclusive set of transition assemblage. The design of such a coherent assemblage of transition instruments may be referred to as "transition management" (Chappin & Dijkema, 2008a). The design normally starts with policy change, which affects actor behaviour, leading to changes in technical elements and eventually performance.

2.4 Types of system change

The types of system change involved in socio-technical system transitions include:

2.4.1 Incremental change

This type of change is the most common and involves updating or improving existing systems – competence enhancing (Innovation management fundamentals, 2014). An incremental change is solely based on existing technologies or processes (Fairweather et al., 2009).

2.4.2 Modular change

Modular change is a significant improvement within a system without changing the basic architecture of the system (Rebecca, Henderson, & Clark, 1990).

2.4.3 Radical change

A radical change is one that substantially involves new technology which normally would not conform to existing system because it introduces new technologies and practices which are radically different from the antecedent (Bleischwitz et al., 2009). Radical innovations are usually confined to niches in the absence of huge landscape pressure because they tend to have a competitive relationship with the incumbent regime (Geels & Schot, 2007).

2.4.4 Architectural change

Architectural change occurs when radical innovations change the existing correlation between technical (nodes and links) and non-technical elements of the system, i.e. the network architecture or value network (Christensen & Rosenbloom, 1995). Such innovations are often a threat to sunk investments and embedded competencies and as such are always controversial and take a long period of intense competition before emerging (Bolton & Foxon, 2010).

2.5 Transition Concepts

The emergence of transitions has been conceptualised in several approaches which include the multi-level perspective (which distinguishes three analytical and heuristic levels), the transition pathways (which results from interaction of dynamics among distinct levels), the multi-phase perspective (which identifies the phases of transition) and the stocks and flows notion (which observes the long-term and short-term developments in system transition). These concepts are discussed in the following sections. The multi-level and the multi-phase perspectives in a transition structure how transitions come about. The key point in the multi-level perspective is that system innovations that lead to system transitions come about through the interplay between dynamics at multiple levels (Chappin & Dijkema, 2009; Foxon, Pearson, & Hammond, 2008; Geels, 2006a; Geels & Schot, 2007).

2.5.1 The Multi-level Perspective

The multi-level perspective (MLP) is a framework of hierarchical levels with heterogeneous configuration of elements that interact (FarmPath, 2014). It is multi-disciplinary combining various fields including but not limited to evolutionary economics, sociology, structuration and neo-institutional theories. Transitions from one set of technologies and the associated practices to another can be described using the MLP levels which define the process over which transitions appear to take place. The MLP distinguishes between three analytical and heuristic levels for system innovation namely (Geels, 2002; Rip & Kemp, 1998);

(1) The macro-level: contains socio-technical landscapes and accounting for exogenous environment, with global and normally slow developments.

(2) The meso-level: holds a patchwork of socio-technical regimes in a dynamic equilibrium and is the locus of established practices and associated rules that stabilise existing systems. It accounts for system stability.

(3) The micro-level: contains technological niches and is the locus for radical innovations, in which new technologies can come into existence and be developed. It consists of spaces for the emergence of new innovations

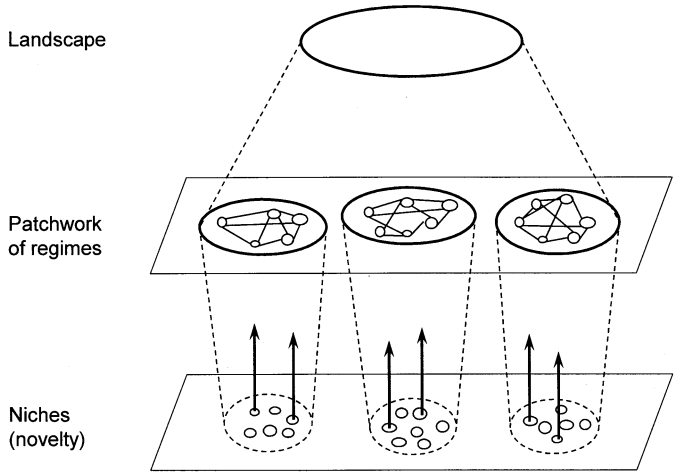


Figure 2.3. The MLP as a nested hierarchy (Geels, 2002)

The three levels form a nested hierarchy with regard to local practices (Geels, 2002; Geels, 2007). Higher levels are more stable than lower levels with respect to the number of actors and degrees of alignment between the elements (Geels, 2011). These levels are not hierarchical descriptions of reality but rather meant as analytical concepts. Transitions in this context occur when innovation on the micro-level evolves and is taken up to modify the mix up of regimes and eventually transforms the landscape on the macro level (Geels, 2002). This concept has been used by several works to describe and analyse past transitions. These three levels are applicable to all major socio-technical systems but here, all definitions and descriptions are made with respect to energy system.

Level 1.   Socio-technical landscape

The socio-technical landscape is the upper most level on the MLP framework. The landscape level highlights not only hard aspects such as technical and material that sustains society, but also includes soft factors of economic conditions, political ideologies and societal trends (A. Smith et al., 2005). Elements in the landscape relate to the material and immaterial set of deep structural trends and slow changing factors such as material infrastructure, macroeconomic factors (e.g. oil prices, economic growth), broad political coalitions, deep cultural and normative values, social patterns, worldviews and paradigms, demography, the natural environment, emigration, wars (Geels, 2011; Kemp, 2009). Therefore, the socio-technical landscape (with a heterogonous set of contextual factors at the macro level) forms an exogenous environment and a broader context in which regimes and niches are situated, which is beyond the direct influence of niche and regime actors, has a deep structuring influence on niches and regimes as well as their interaction but itself cannot be changed directly by actors (Geels, 2011; Rip & Kemp, 1998). Changes at the landscape level usually take place slowly (usually decades) and are the key philosophy behind policy making (Geels & Schot, 2007; Shackley & Green, 2007).

Current societal landscape may be given by a concept of economic growth which has relied since the industrial revolution on fossil fuels, although with major shifts from coal to oil and natural gas. Since the mid-1980s, concerns over carbon dioxide emissions from fossil fuel use have grown, moving environmental concerns away from fossil fuel depletion to the adverse consequences of its utilisation. As a result, the IPCC produced its first assessments of anthropogenic climate change in 1990 indicating current and possible future impacts of carbon emissions (IPCC, 1990). From the early 1990s, the UNFCCC and its Kyoto Protocol of 1997 (which came into force in 2005), has emerged as the dominant policy framework in European Union countries and hence constitutes the relevant policy landscape (UNFCCC, 2014d).

Level 2. Socio-technical regime

The next level on the MLP framework is the socio-technical regime forming the meso-level (Kemp & Rotmans, 2005). A socio-technical regime represents the dominant way (established practices and associated rules) by which a particular societal function is delivered (Geels, 2012; Robinson et. al., 2011). It refers to collective intellectual routines in an engineering community and explained patterned development along predictable technological trajectories (Geels, 2010; Geels & Schot, 2007). Socio-technical regime consists of "a set of technologies embedded in a social, political and institutional context with its associated regime-specific set of rules, procedures, habits and practices" (Shackley & Green, 2007). The socio-technical regime is an extended version of a technological regime described by Nelson and Winter's (1982) which refers to cognitive routines shared in an engineering community guiding research and development activities in specific directions, leading to development along technological trajectories (Geels, Hekkert, & Jacobsson, 2011). Socio-technical regimes are broader in scope and include all established patterns and structures, such as technology, rules and regulations, markets and user practices, institutions, organisations and networks, supply and maintenance networks, infrastructure, cultural meaning and routines (Geels, 2004; Loorbach, 2010). Therefore, elements in socio-technical regimes are not limited to engineering practices and firms but also include all relevant social groups like engineers, policy makers, users, scientists, media, firms, civil society and special-interest groups who contribute to patterning of technological development (Geels, 2012; Geels, 2004; Bijker, 1995).

The sociotechnical regime concept accommodates this broader community of social groups and their alignment of activities (Geels & Schot, 2007). This cluster of heterogeneous elements can be grouped under six convenient dimensions namely; technology, science, policy, markets and user practices, cultural meaning, industry and production networks (Geels, 2007). Further grouping by Geels (2004) reduces these elements into the three dimensions of actors, systems and rules/institutions. Actors can be government, business, scientists, nongovernmental organisations (Loorbach, 2010). Systems can be the material or technical elements. Rules can be one of the three interlinked pillars; formal rules which constrain behaviour and regulate interactions, normative rules which confer values, duties, codes of conduct, norms, role expectations, rights and responsibilities, and finally cognitive rules which constitute the models of reality, belief systems, bodies of knowledge, guiding principles, search heuristics and the frames through which meaning or sense is made (Scott, 1995 in Onsongo, 2013; Geels, 2006a). All these elements fit into one of the two arms of a regime; the social or technical components, and hence the term 'socio-technical' (ST) regime.

Socio-technical regimes account for the stability of existing socio-technical systems (Geels & Kemp, 2007). It is at this level that path-dependency and lock-in may take place, whereby technological regimes emerge alongside institutional and social changes (mainly due, amongst other things, to increasing returns to the scale of adoption and positive feedback mechanism) (Arthur, 1989; Falcone, 2014; Greenacre, 2012; Hillman & Sandén, 2008; Shackley & Green, 2007). Therefore, socio-technical transitions do not easily occur because existing systems are stabilised by mechanisms on the three dimensions of actors, systems and rules/institutions (Geels, 2010; Unruh, 2000). These mechanisms are vested interest (from the actors), regulations/standards/cognitive routines (from the rules/institutions), sunk investments and technical complementarities among components (on the system) (Berkhout, Wieczorek, & Raven, 2011). Existing trajectories are stabilised in many ways: cognitive routines that blind engineers to developments outside their focus (Nelson and Winter, 1982), regulations and standards (Unruh, 2000), adaptation of lifestyles to technical systems, sunk investments in machines, infrastructures and competencies (Tushman & Anderson, 1986; Christensen, 1997). These mechanisms which grow with regimes are responsible for their stability and inertia resulting from the linkages and alignments between heterogeneous elements and often act as resistance to their radical transformation and rather tend to orientate the regime towards incremental innovation along predictable trajectories (Geels, 2011; McMeekin & Southerton, 2012). For transitions to occur, each of the stabilizing forces needs to be unlocked to allow new alternative regimes to emerge in a dominant position (Berkhout et al., 2011).

Each regime is unique in terms of its content and context. According to Geels and Schot (2007), a socio-technical regime can be defined at one of many empirical levels. For instance, in the electricity domain a regime might be considered at the level of primary fuel (coal, oil, or gas) or at the level of the entire system (production, supply and consumption). What looks like a regime change at one level may appear merely as an incremental change for a broader regime at another level. A collective shift of ST regime to give another regime is termed socio-technical transition. The new regime often consists of different states of elements.

Level 3: Technological niche

The lowest level on the multi-level perspective is the technological niche which forms the micro-level where fundamental innovations exist. It is a system level that exists below the regime and forms the locus where novelties emerge (Geels, 2005b). The niches are actually slots or spaces of local practices that constitute the potential components of a new regime. These radical novelties are initially unstable sociotechnical configurations with low performance/efficiency and thus, in no way can they compete with their existing counterparts in the dominant regime (Geels, Hekkert, & Jacobsson, 2008). Because of their usually poor cost effectiveness, niche innovations may not be suitable for a large-scale market adoption at the early stage. Nevertheless, they will continue to exist because the niches act as ‘incubation rooms’ protecting the novelties against mainstream market selection (Schot, 1998; Kemp et al., 1998). Such protection is necessary in view of their low cost-performance factors (Geels & Schot, 2007; Verbong & Geels, 2008). Variations to and deviation from regular practices in an existing regime occur at this level because of the usual mismatch between niche-innovations and existing regime dimensions (Geels, 2010).

Through learning process, these novelties reach a maturity level and can be supported by outsiders for adoption. Sometimes these new technologies displace the existing ones and become the new dominant technologies within the regime (Shackley & Green, 2007). New innovations come to exist in the regime as a result of their perceived need under certain circumstances but may have a hard time to penetrate (Geels & Schot, 2007). They are carried and developed by small networks of dedicated actors, often outsiders or fringe actors (Foxon, Hammond, & Pearson, 2010). The expectation of niche actors is that with time, the novelties will be adopted by the regime either as add-ons or as alternatives (Geels, 2007). Therefore, technological niches acting as incubation rooms for novelties shield new technologies from mainstream market selection, providing locations for various learning processes, and space for building social networks supporting the technologies (Berkhout et al., 2011; Geels, 2011; Schot, 1998).

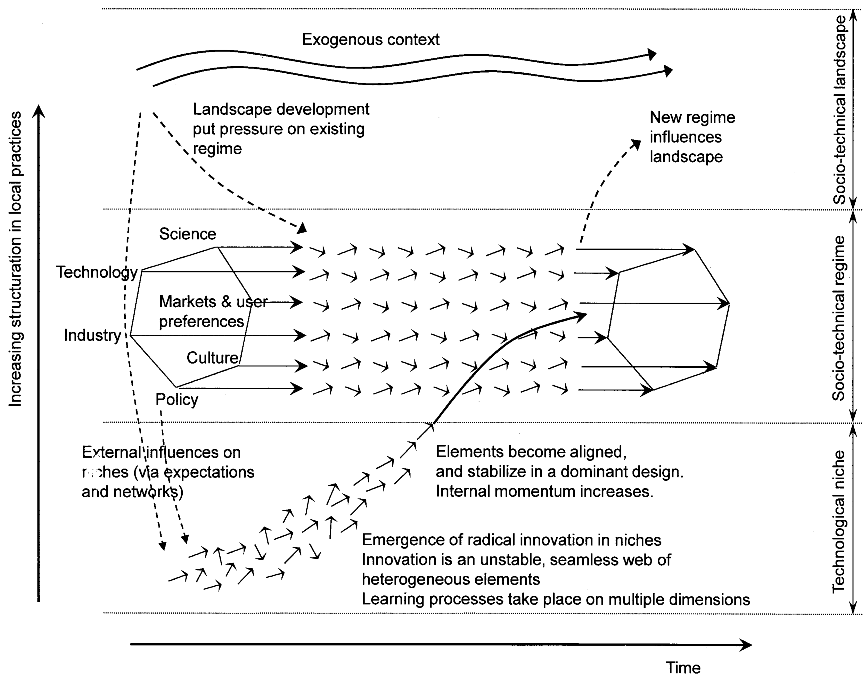


Figure 2.4. The MLP framework of system transition (Geels & Schot, 2007)

Figure 2.4 above provides an ideal-typical representation of how the three levels interact dynamically in the unfolding of socio-technical transitions. Although each transition is unique, the general dynamic pattern is characterised by transitions resulting from the interaction between processes at these levels thus: (a) niche-innovations build up internal momentum, (b) changes at the landscape level create pressure on the regime, and (c) destabilisation of the regime creates windows of opportunity for niche innovations (Geels & Schot, 2007). The application of the MLP has been illustrated with many historical case studies of transitions, such as in land transport and in sewers and sanitation as well as in studies of contemporary and future transitions to sustainability, e.g. in electricity, mobility and ‘green’ cars (Whitmarsh, 2012; Geels, 2005c; Geels, 2006b; Geels, 2012).

Some of the major historical changes in energy technologies have been from charcoal production, to use of coal in furnaces and boilers with steam engines, to the internal combustion engine, including the turbojet engine in aviation, and the gas and steam turbine combined cycle (CCGT). These past technological innovations have involved a combination of fuel types (towards those fuels with a higher hydrogen-to-carbon ratio, i.e. from wood to charcoal to coal to oil to natural gas) and technologies which utilize those fuels with ever greater efficiency (Ausubel and Langford, 1997). The MLP indicated that there is no simple causality or single driver in transitions. Transitions happen through multiple processes in multiple domains, levels and dimensions which link together and reinforce each other (circular causality) (Geels, 2005b; Geels, 2011; Geels, 2012; Geels & Schot, 2010). The table below summarises the activities in the three heuristic levels.

Table 2.1. Summary of the MLP framework dynamics

Landscape	**Regime**	**Niche**
Macro-economic trends E.g. globalisation, oils crisis	Changes in rules e.g. belief systems, problem agenda's, Guiding principles, search heuristics; relationships, behavioural norms; regulations, standards, laws	Learning processes e.g. learning processes have stabilised in a dominant design
Socio-economic trends E.g. recessions, unemployment developments	Changes in technologies e.g. in the case of electricity: resources, grid, generation plants	Price–performance improvements E.g. price–performance improvements have been made and are believed to continue to improve
Macro-political developments e.g. the ‘philosophy’ behind policy making	Changes in social networks e.g. new market entrants gain in importance compared to incumbents	Support from powerful groups E.g. powerful actors have joined the support network
Deep cultural patterns E.g. trend towards more ‘individualisation’		Establishing market niches E.g. innovation is used in market niches

Source: Kern (2011); Rip and Kemp (1998); Geels (2002); Geels and Schot (2007); Shackley and Green (2007).

2.5.2 Transition pathways P

In the analysis of transitions, it is important to distinguish transition concepts by type. The idea of the multi-level perspective is that transitions come about through interplay among processes at multiple levels: 1) changes at the landscape exerts considerable pressure on existing regime, 2) it is perceived that these pressures cannot be dealt with by incremental innovation in the existing regime, resulting to regime destabilisation and creating windows of opportunity for niche innovations, 3) niche innovations are reasonably developed for adoption in the regime (Schot & Geels, 2008). Transitions typically occur through the interaction of two or more of the three MLP levels. Geels and Schot (2007) and A. Smith et al. (2005) suggested different typologies based on the levels of the landscape pressure and maturity niche of niche innovations, and the timing of landscape pressure action with respect to maturity level of niche innovations. Bergman et al., (2008) defines a transition pathway as “a minimal sequence of mechanisms and events needed to generate a transition, including a description of the initial and final states of the system.” The regime is the main level where transitions occur while the landscape and niche are considered as derived concepts (Geels, 2011). The five transition pathways are discussed as follows.

P00 Reproduction pathway

The first transition pathway is called reproduction processes. Reproduction pathway is a result of a regime reproducing itself in the absence of a disruptive landscape pressure without the introduction of new innovations into regime. This implies that reproduction is a regime only transition. The absence of landscape level means there is no pressure influence on regime actors to change orientation and/or adopt new innovations. However, the regime is dynamically stable in the sense that dynamics such as market competition, new investments etc. have been in existence. The aim is only to optimise a system without tempering with the basic regime settings. Regime players often have the impression that minor problems that may arise within the regime could be resolved using internal solutions without the need of any external input. Achievements in reproduction are a result of invisibly slow accumulation of modifications through small and continuous innovation improvements. It is assumed that reproduction (i.e. incremental improvements to existing technologies) will continue in any given socio-technical regime (Rosenberg, 1982; Geels & Schots, 2007; Shackley & Green, 2007).

P01 Transformation pathway

Transformation occurs as a result of interactions between the regime and the landscape without a substantial involvement of the niche level. The regime experiences a moderate landscape pressure at a time when niche innovations are not sufficiently developed. These pressures are usually translated by societal pressure groups and social movements. In response to the pressure, regime actors modify the direction of development paths and innovation activities by using the innovations as add-ons to solve local problems. These modifications occur without changing the basic architecture of the existing regime. In this pathway, regime actors survive as new regimes emerge from the old regime through cumulative adjustments and gradual trajectory realignments. The new regime emerges out of the old one through cumulative adjustments and reorientations. In this pathway, government intervention can be used to focus and encourage the pace of change (Kamp et. al., 2010; Shackley & Green, 2007; Verbong & Geels, 2010).

P02 Reconfiguration pathway

This pathway is a result of interactions among all the three levels and occurs when a system changes through cumulative component changes and new combinations through the adoption of niche-innovations. Reconfiguration take place when innovations developed in niches trigger further adjustments at the regime level (Kamp et. al., 2010). This pathway involves the replacement of a set of interlocking technologies by an alternative array of inter-related technologies which fulfil the same, or similar, functions. The alignments of alternative interlocking technologies in response to huge and continually emerging landscape pressure result in new regime architecture and broader changes in the system.

Symbiotic innovations, which developed in niches, were initially adopted in the regime as supplementary components to solve local problems. At this point these alterations were not enough to trigger changes in regime rules and the basic architecture normally remains unchanged just like the transformation pathway. Overtime, learning processes may reveal potential roles of novelties in the regime, opening up windows of opportunity for niche-innovations. Subsequent innovations further lead to social and technical changes and under continued landscape pressure, gives rise to large-scale re-alignment and re-orientation of the socio-technical regime. The reconfiguration pathway can best be described under the context of a distributed socio-technical system with multiple interrelated technologies such as agriculture (soil enrichment, pesticides, canning, etc.), hospital (X-ray, laboratory, theatre, etc.), etc. (Bergman et al., 2008; Foxon et al., 2008; Geels & Schots, 2007; Haxeltine et al., 2008; Shackley & Green, 2007).

P03 Substitution pathway

Substitution occurs as a result of interactions among all the three levels on the MLP. The regime experiences enormous pressure from the landscape at a time when a niche innovation is fully matured and is ready to break through. Before this pressure, the innovation remains stuck in the niche because the regime is strongly entrenched, unwilling to give up to an alternative technology. But with the development of the intense pressure on the regime, windows of opportunity for the new technology are created, allowing it to compete favourably with the incumbent dominant technology. The niche innovation will break through and ultimately replace the existing regime. Therefore this pathway has a 'technology push' character whereby the existing dominant regime is gradually displaced by the emerging niche technology, resulting to radical transformation of the incumbent regime. Technological substitution is a direct replacement of one dominant technology within the socio-technical regime by another (Nunez-Lopez, 2014 ; Haxeltine et al., 2008; Shackley & Green, 2007).

P04 De-alignment/re-alignment pathway

De-alignment/de-alignment occurs through the interplay among all the three levels on the MLP. It is characterised by a divergent, sudden and huge disruptive landscape pressure on a regime at a time when a number of immature niche innovations exist. The pressure is so enormous to cause regime destabilisation, and subsequent erosion or de-alignment of existing regimes because actors lose faith in the usual solutions. This creates space for competition between the dominant technology within the regime and a number of other competing options which have different performance characteristics. This leads to uncertainties in choice and adoption, causing the exploration of different possible trajectories. In this pathway, there is no clear substitute for the eroded regime and this leaves space for the emergence and co-existence of multiple innovations that compete for attention and resources. This is eventually resolved through the emergence of one niche-innovation (after a prolonged period of competition) which becomes dominant, forming the core for re-alignment of a new regime and re-institutionalisation. This pathway is characterised by a long period of experimentation, co-existence, competition and learning before the new regime emerges. This pathway results to a major restructuring of the system in terms of new guiding principles, beliefs and practices (Bergman et al., 2008; Foxon, et al., 2008; Verbong & Geels, 2008).

2.5.3 Transition pathways' representation

A. Smith et al. (2005) develop a scheme of socio-technical transformations using two axes to define the context of transitions. The scheme presupposes that transitions fit within a specific quadrant to represent the four main transition pathways in Geels and Schot (2007) typology as depicted in Figure 2.5 below. Their characteristics are summarised in Table 2.2.

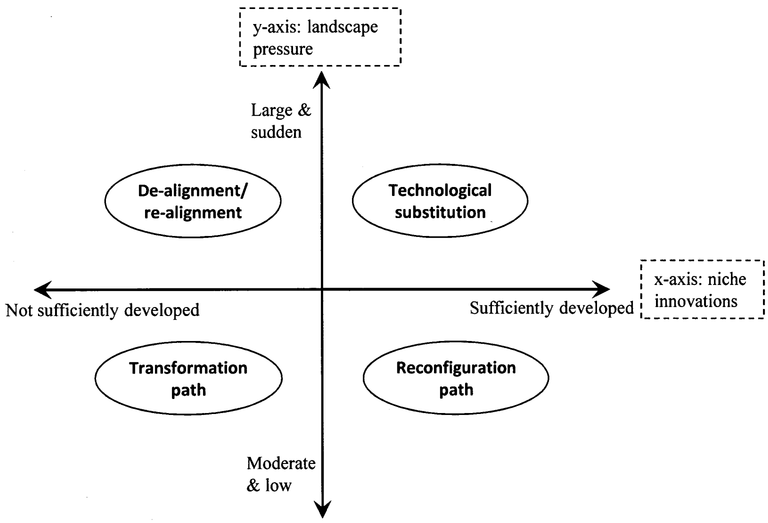


Figure 2.5. Quadrant representation of transition typology (Geels & Schot, 2007; A. Smith et al., 2005)

Table 2.2. Characteristic summary of the four transition pathways

Pathway	**Transformation**	**Reconfiguration**	**Substitution**	**De-alignment/ De-alignment**
MLP levels involved	Landscape & regime	Landscape, regime & niche	Landscape, regime & niche	Landscape, regime & niche
Levels of landscape pressure/niche technology development	Moderate/ partial	High/partial	High/full	Unbearable/ partial
Transition mechanism	Cumulative use of add-ons	Cumulative component adjustment	Technology push character	New regime emergence from competing niches
Fate of old regime	Survival	Minority	Minority	Extinction
Type of regime change	Incremental	Radical	Radical	Radical

Source: Geels & Schot (2007).

2.5.4 The Multi-Phase concept

The multi-phase concept implies that transition paths are highly non-linear, involving different phases shifting from one dynamic equilibrium to another. Therefore, the evolving pathway scenarios can be further sub-divided into four transition phases, i.e four transition phases can be identified in each transition pathway (Loorbach & Rotmans, 2006; Rotmans et. al., 2001):

1. A *predevelopment phase* is one of dynamic equilibrium with a great deal of activities at the individual level but changes are hardly noticeable at the system level.

2. The *take-off phase* where the process of change starts to occur at the system level.

3. A *breakthrough or acceleration phase* in which visible structural changes take place at the system level.

4. The *stabilisation phase* which marks the end of transition, where speed of change decreases and a new dynamic equilibrium is reached.

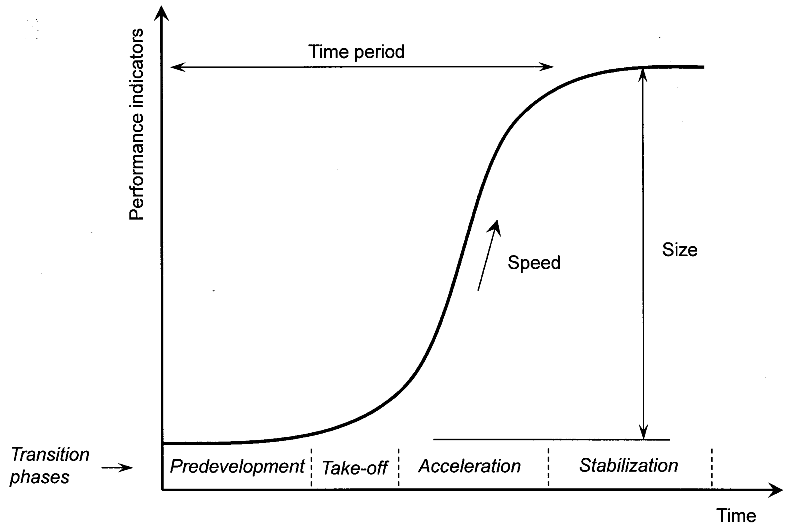


Figure 2.6. The MLP concept: phases and indicators in transitions (Rotmans et. al., 2001)

Each of these phases can be linked to particular mechanisms. If the phenomenon of transition is examined from a system's point of view, what becomes apparent is a transformation from slow dynamics to fast and unstable processes, then to relative stability. The new equilibrium is a dynamic equilibrium, i.e. there is no status quo, because a lot is changing under the surface. During the quick period of growth, the acceleration is mainly the result of positive feedback mechanism in the system that reinforces each other (Rotmans et. al., 2001). Given an indicator or a set of indicators for transition, three system dimensions may be identified as shown in Figure 2.6; the *time period* of a transition, the *speed* and the *size of the change*. The four phases indicate that transitions follow a definite pathway and therefore, designing this pathway is equivalent to designing a transition. However, this requires unambiguous measurable performance indicators because the pathways are directly linked to indicators as shown on the vertical axis (Chappin & Dijkema, 2008a). In principle, it is possible to have different transition pathways to the same equilibrium level or the same transition to be realised in different pathways (Loorbach, 2004; Loorbach, 2010).

2.5.5 Stocks and flows concept

The principle of accumulation states that all dynamic behaviour in the world occurs when flows accumulate in stocks (Richard, 2012). According to Rotmans et al., (2001), “the system approach implies thinking in terms of stocks and flows.” Complex systems have a hierarchy of levels characterised by higher but slower changing levels and lower but faster changing levels (Holling, 2001). Stocks are system elements that accumulate in the long-term and are described in terms of quantity and quality while flows are the elements that change relatively faster in the short-term (Rotmans et al., 2001). Therefore, stocks and flows can be related to the slow (longer periods) and fast (shorter periods) changing properties of a complex system respectively. In socio-technical systems, stocks represent the physical infrastructure and institutions, while flows represent activities of actors, movements of goods and services.

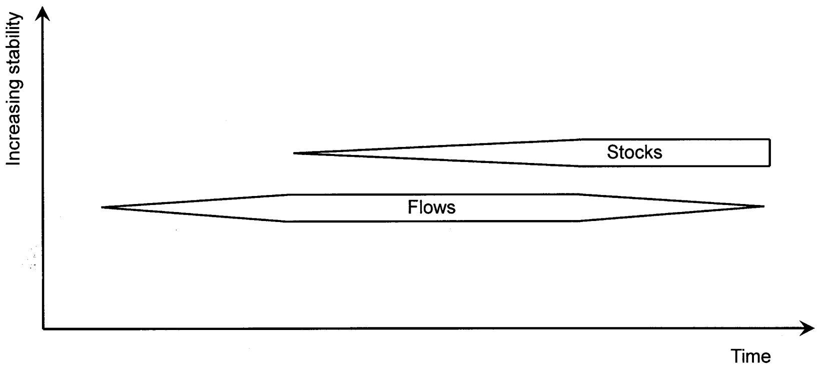


Figure 2.7. The stocks-flows concept (Based on Rotmans et al., 2001)

Figure 2.7 shows the time relationship between stocks and flows. In the beginning of a particular system transition, the transition flows begin to change and accelerate to a peak level without seeing any clear changes on the stocks. This may be related to the predevelopment phase of the transition. When the flows reach a certain maximum point, they will trigger a change on the stocks. The flows will maintain this approximately constant activity level for a period of time while the stocks continue to grow to a certain maximum level during this period. This may be related to the take-off and acceleration phases of the transition. At the point where stocks have reached their maximum point, the flows responsible for the transition will begin to reduce to another state of dynamic equilibrium while the stocks have reached their full growth and stability.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

The approach to the research involves both theoretical and numerical applications of the MLP and MPP in determining the current status of transitions in the UK's road transport and power generation sectors. This follows an exhaustive study of how the transition pathways behave in a sequence during a transition. The criterion for determining the energy consumption/emission sectors that can serve as case study sectors for the research is the historical level of GHG emissions by the sectors. Figure 3.1 below shows the methodological chart with low carbon energy transition as the research area, socio-technical transition pathways constituting the literature body, the UK's road transport and power generation as the two case sectors (section 3.1), the sectoral analytical approach and the end state of the transition.

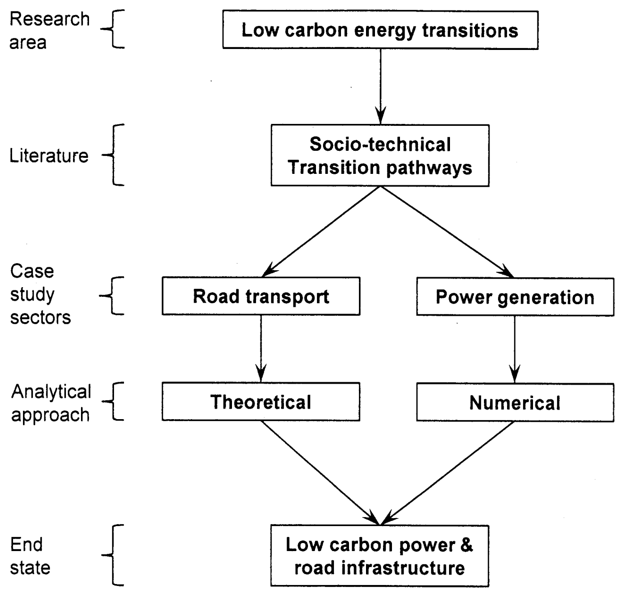


Figure 3.1. Methodological flow chart

3.2 Energy consumption and emission sectors

Energy is an underlying requirement for the fulfilment of all social functions which are pre-conditions for human existence, including but not limited to shelter and clothing, food and drink, mobility, etc. The UNFCCC (2014c) distinguishes sectoral scopes in the energy consuming and emission sectors according to five categories:

1) Energy sector;

- Public electricity and heat production,
- Petroleum refining,
- Manufacture of Solid Fuels and Other Energy Industries.

2) Transport;

- Road Transportation,
- Civil Aviation,
- Railways,
- Navigation,
- Other Transportation.

3) Manufacturing industries and construction;

- Iron and steel
- Non-ferrous metals
- Chemicals
- Pulp, paper and print
- Food processing, beverages and tobacco, etc.

4) Residential/Commercial/Institutional buildings;

5) Agriculture/ Forestry/ Fisheries;

Table 3.1. Sectoral GHG emissions from fuel combustion in the UK (mtco2eq)

	Energy sector		**Transport**				
Year	**Public Electricity and Heat Production**	**Petroleum Refining, Manufacture of Solid Fuels and Other Energy Industries**	**Road Transportation**	**Civil Aviation, Railways, Navigation & Other Transportation**	Manufacturing industry and construction	Commercial/ Institutional/ Residential buildings	Agriculture/ Forestry/ Fisheries
1990	205.95	31.80	110.65	5.68	106.51	104.64	5.84
1991	202.58	32.96	109.87	5.64	108.58	116.07	5.87
1992	190.54	33.76	111.34	5.65	105.38	112.84	5.92
1993	172.89	34.98	112.64	5.64	102.77	116.35	5.94
1994	168.72	36.97	113.28	5.59	101.96	111.21	6.01
1995	165.47	38.42	112.32	5.85	98.56	106.82	5.98
1996	165.02	40.47	116.43	6.14	99.22	120.09	6.08
1997	151.99	40.68	117.78	6.26	97.57	110.97	5.99
1998	157.10	41.30	116.99	6.57	96.43	112.61	5.79
1999	148.85	40.25	117.80	6.77	98.34	112.76	5.76
2000	160.40	39.29	116.91	6.89	98.48	112.24	5.41
2001	170.71	39.07	116.81	7.03	97.33	115.13	5.47
2002	166.41	41.39	119.12	7.09	88.39	107.67	5.42
2003	175.56	39.77	118.70	7.19	89.93	108.99	5.39
2004	175.14	39.32	119.85	7.47	88.82	110.96	5.14
2005	175.00	38.89	120.49	7.83	89.23	106.58	5.18
2006	184.34	37.63	120.43	7.74	87.03	101.87	4.85
2007	180.12	36.35	123.28	7.71	86.07	97.08	4.70
2008	175.04	35.55	116.23	7.54	81.12	99.39	4.79
2009	153.22	34.19	112.09	7.15	70.06	93.18	4.67
2010	158.72	34.44	110.73	6.96	69.72	106.10	4.81
2011	146.34	33.74	109.26	6.96	65.34	84.76	4.78
2012	160.60	30.98	108.95	6.77	65.72	94.21	4.73

Source: (UNFCCC, 2014c)

These sectors cause harmful emissions as a result of combustion of energy during use (Table 3.1). It is important to look at the nature of energy needs across all socio-technical regimes. Energy on its own does not hold any distinct socio-technical regime but rather, the provision of physical sources of energy is a basic condition for all socio-technical regimes to function. In some cases energy is a more obvious component of the regime, e.g the socio-technical regime within aviation where energy provision is a specific, tailored, component of the system. Whereas for the socio-technical systems that are involved in the provision of education, energy provision is of a non-specific form drawing their needs from invisible energy supply infrastructures (Shackley & Green, 2007). Therefore, it is also important to look at how the various sectors emit harmful emissions.

3.2.1 Sectoral GHG emissions

1) Energy sector emissions

The energy sector emissions come from the combustion of fossil fuels in power plants (for generate electricity and heat), petroleum refineries (for crude oil refining) and in other energy industries (for the manufacture of solid fuels). Of these sources, the main emitting sector is the power generation sector. The main pollutant from the power sector is CO2, with small amounts of methane (CH4) and nitrous oxide (N2O). Petroleum refinery emissions are a result of combustion of fossil fuel in process heaters and boilers during crude oil refining process. In addition to the combustion-related sources, certain processes such as fluid catalytic cracking units (FCCU), hydrogen production units, and sulphur recovery plants, also contribute process emissions of CO2. Asphalt blowing and flaring of waste gas also contributes to the overall CO2 emissions at refineries (Sims et al., 2007; Steen, 2015; USEPA, 2010; USEPA, 2015).

2) Transport sector emissions

Emissions from transportation come from the combustion of fossil fuels in the internal combustion engines for locomotion. The main GHG from transportation is CO2, with relatively small amounts of methane (CH4) and nitrous oxide (N2O) as well as hydrofluorocarbon (HFC) emissions. The largest proportion of transport-related GHG emissions (above 90%) are due to road transport resulting from consumption of petroleum-based products, such as gasoline and diesel, by passenger cars, light-duty and heavy-duty trucks (UNFCCC, 2015; USEPA, 2015).

3) Manufacturing industry and construction emissions

The manufacturing industry and construction sector consumes energy for the production of goods and raw materials. Emissions from this sector contain both the direct emissions from combustion of fuels at the facility and indirect emissions that occur off site, but are associated with the facility's use of energy. Direct emissions are produced by burning fuel (mainly fossil fuels) for power or heat, while indirect emissions are produced by burning fossil fuel at a power plant to produce electricity for industrial facilities to power buildings and machinery (Brown, 2012; USEPA, 2015).

4) Residential, commercial and institutional emissions

The residential and commercial sectors include all homes and commercial businesses, but exclude agricultural and industrial activities. GHG emissions from this sector largely come from the combustion of natural gas and petroleum products for heating and cooking needs (which emit carbon dioxide-CO2, methane-CH4, and nitrous oxide-N2O). Natural gas forms the largest source of emission in this sector, accounting for about 81% of the direct fossil fuel CO2 emissions. Other GHG sources come from the management of waste and wastewater; organic waste in landfills which emits CH4, wastewater treatment plants which emit CH4 and N2O. Also, fluorinated gases (mainly hydrofluorocarbons - HFCs) can be released from refrigerants (air conditioning and refrigeration systems) in homes and businesses during servicing and/or from leaking equipment. The indirect emissions from this sector results from the production of electricity for consumption by businesses and homes (USEPA, 2015).

5) Agriculture/ Forestry/ Fisheries

Agricultural activities are the cultivation of crops and rearing of livestock for food. Agriculture releases to the atmosphere significant amounts of CO2, CH4, and N2O (Cole et al., 1997; IPCC, 2001; Paustian et al., 2004). The sector contributes to GHG emissions in many ways. Management of agricultural lands (lands used for agricultural production) such as fertiliser application, irrigation and tillage methods contribute to N_2O emissions through the microbial transformation of nitrogen in soils and manures (Oenema et al., 2005; Smith & Conen, 2004). CH_4 and N_2O are produced when organic materials decompose under deficiency of oxygen, e.g. CH_4 from fermentative digestion by ruminant livestock, especially cattle (enteric fermentation process), CH_4 and N_2O emissions from burning crop residues and manure management which depends on the mode of storage, and CH_4 from rice grown under flooded conditions (Mosier et al., 1998). CO_2 is released largely from microbial decay or burning of plant litter and soil organic matter (P. Smith, 2004; Janzen, 2004). Agriculture accounts for about 10-12% of total global anthropogenic emissions of GHGs (P. Smith, et al., 2007).

Biological carbon sequestration is the storage of carbon in plants (absorbing atmospheric CO_2 as they grow, storing some of the carbon throughout their lifetime) and soils (depending on how the soil is managed) (National Wildlife Refuge System, 2015; P. Smith et al., 2014). Biological sequestration is referred to as a GHG "sink" because it removes CO_2 out of the atmosphere (Warren, LeQuéré, & Price, 2015). However, emissions or sequestration can occur in this sector depending on the nature of land use change, e.g. cultivation of new areas to become cropland, conversion of former cropland into grassland, or growth of forest (Global Environment Facility, 2015; P. Smith et al., 2014). In many developed countries, land use, land-use change, and forestry (LULUCF) sector is a net GHG sink (Iversen, 2014; USEPA, 2015). However in some countries (especially developing countries) where large areas of forest land are cleared for agricultural purposes or for settlements, the LULUCF sector can be a net source of GHG emissions (Iversen, 2014; USEPA, 2015). Emissions from the fisheries sector come from combustion of fuels in vessels and boats during fishing activities (Seas At Risk, 2015).

3.2.2 Selection of case study sectors

The selection criteria of carbon emitting sectors for the case study will depend on the magnitude of sectoral GHG emissions from the year 1990. By observing the emission trends of the five sectors in the UK economy between the period 1990-2012, it is obvious that the electricity and heat sector and the road transportation sector are the highest emitters as shown in Figure 3.2. Therefore, these two sectors are considered for the low carbon transition pathway analysis in this work.

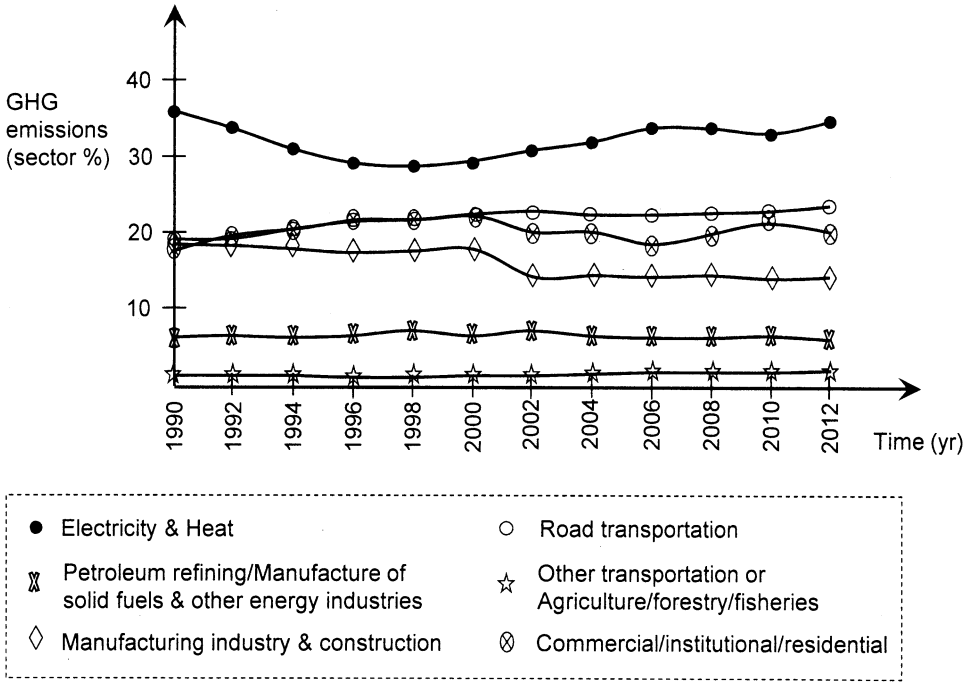


Figure 3.2. Sectoral GHG emissions in the UK (UNFCCC, 2014c)

3.3 Decarbonisation strategies

The UNFCCC in its CDM methodology booklet categorises energy system and decarbonisation strategies according to the relevant sectoral scopes and type of mitigation activities (UNFCCC, 2014b).

Categorisation in terms of type of mitigation activity includes:

1) Displacement of a more-GHG-intensive output:

1a. Renewable energy;

1b. Low carbon electricity.

2) Energy efficiency;

3) Fuel switch;

4) GHG destruction.

1) Displacement of a more-GHG-intensive output

1a) Renewable energy: This category includes the use of various renewable energy sources such as hydro power plant, wind power plant, solar, biomass, etc.

1b) Low Carbon Electricity: This encompasses mainly greenfield electricity generation based on less carbon intensive fuel such as natural gas. A typical example is the construction of a Greenfield natural-gas-fired power plant.

2) Energy Efficiency: The category energy efficiency includes all measures aiming to enhance the energy efficiency of a system whereby a specific output or service requires less energy consumption. Waste energy recovery is also included in this category.

Examples include:

- Conversion of a single cycle to a combined cycle gas-fired power plant;
- Installation of a more efficient steam turbine;
- Use of highly efficient refrigerators or compact fluorescent lamps;
- Recovery of waste heat from flue gases;
- Recovery and use of waste gas in a production process.

3) Fuel Switch: In general, fuel switch measures in this category will replace carbon-intensive fossil fuel with a less-carbon-intensive fossil fuel, whereas a switch from fossil fuel to renewable biomass is categorised as ‘renewable energy’.

Examples include:

- Switch from coal to natural gas;
- Feedstock switch from fossil sources of $CO2$ to renewable sources of $CO2$
- Use of different raw material to avoid GHG emissions.

4) GHG destruction: Destruction covers activities that aim at the destruction of GHG, including capture or recovery of the GHG.

Examples include:

- Combustion of methane (e.g. biogas or landfill gas);
- Catalytic $N2O$ destruction

In general, decarbonisation strategies involve innovations to reduce demand, fuel switching/retrofitting (R&D), and investment in new technology.

3.4 Mode of Data Collection

Since collecting high-quality data is the central objective of every study, selecting an appropriate data and information collection strategy is a critical step of the research process. Data on primary energy consumption, electricity generation, carbon emissions, energy infrastructure as well as existing relevant policy are considered crucial. Data and information collection involving but not limited to the following:

1) Government departments and agencies like CCC, DECC, DEFRA, DfT, etc;

2) NGOs and multinational bodies like, World Bank, United Nations, IEA, etc;

3) Websites and articles from the internet.

CHAPTER 4

SEQUENTIAL BEHAVIOUR OF TRANSITION PATHWAYS

4.1 Introduction

Transitions are initiated by landscape development and driven by complementary changes at all the three levels; landscape, regime and niche levels (Geels, 2002; Genus & Coles, 2008). Landscape pressure exerts its weight on regime, destabilizing it to form cracks or windows of opportunities where niche contents (new innovations) pour in. With time, these new introductions (niche elements) into the existing regime form part or whole of the new regime. The pathways to these changes depend on the measure of the landscape and niche developments levels at the point of landscape action (at the start of transition), which determines the type of system change to be involved. Since changes at both landscape and niche levels with respect to transitions are forward oriented, a possible sequence for the pathways can be defined in the same orientation. Geels and Schot (2007) indicated that the possible sequence of the four transition pathways is either T-R-S-D/R (Transformation-Reconfiguration-Substitution-De-alignment/Re-alignment) or T-R-D/R-S depending on a number of factors relating to landscape pressure P_L and niche maturity γ_n beyond R. This chapter builds on this notion by advancing discussions on the concept of the alternate sequences and outlining the determinants of the sequence of transition pathways.

The aim of this chapter is to elaborate the characteristics of the pathways, outline the factors which determine the pathway sequence and simplify its presentation. The first objective is to describe in more details, the different transition phases of the pathways, their advantages and disadvantages based on literature. The second objective is to provide a ranking of the dynamics in the four transition pathways namely; transformation (T), reconfiguration (R), substitution (S) and de-alignment/re-alignment (D/R) while outlining the determinants of pathway position in the sequence. The third objective will be to provide graphical illustrations of the relationships between landscape pressure development, niche development and regime changes (transitions). The purpose is to study the successive linkage of transition pathway scenarios assuming the drivers of change have been established. Therefore, a mere mention of 'technology emergence' will also mean its emergence in association with the relevant actors and rules/institutions. The reproduction pathway is not included in the analysis because it is always in existence even without a disruptive landscape pressure (Rosenberg, 1982).

4.2 Analysing the transition pathways

The previous chapter looks into literature concerning transition pathways. The question will be what are the similarities and differences among the pathways? What is the possible sequence(s) in these pathways if a transition should cover all the pathways? The roadmap to the pathway analysis will follow the direction of landscape pressure increase and cost-performance improvements of niche technologies (in respect to regime technologies). This is because the driving force in regime transitions is strongly dependent on changes in the two MLP boundary levels; the landscape and niche.

4.1.1 Transition characteristics of the pathways

The transformation pathway T has the quality of absorbing and personalizing niche technologies (NTs) while the regime basically (architecturally) remains unchanged, thus the interaction of niche-regime technologies during transitions and the co-existence of new/old regime technologies (RTs) after transition. A transition that goes beyond the transformation pathway (in landscape pressure and/or niche maturity levels) begins to substantially engage NTs into the regime. The reconfiguration R has the quality of absorbing, personalizing and eventually releasing (ejecting) NTs in the regime, while changing the basic architecture.

Similar to T, R is also characterised by the interaction of niche-regime technologies during transitions and the co-existence of new/old RTs after transition. In the substitution S, an NT emerges and pushes a dominant RT, eventually replacing it and making it a minor, thus a short period of niche-regime interaction at the beginning followed by a proper interaction and co-existence of new/old RTs during and after transition. The de-alignment/re-alignment pathway (D/R) does not have interaction/co-existence characteristics of niche-regime or new/old regimes during and after transitions because existing regimes instantly give way to alternative niches just as transition begins owing to the highly disruptive nature of the landscape pressure. A dominant technology emerges from alternative and competing niches in the absence of old dominant RTs.

Table 4.1. Relative characteristics of transition pathways

Pathway		**Transformation**	**Reconfiguration**	**Substitution**	**De-alignment/ Re-alignment**
Landscape pressure P_L		moderate/spread	high/spread	very high/ concentrated	unbearable/ concentrated
Maturity of niche technology at P_L inception		low	moderate	full	moderate
Niche-regime co-existence during transition		present	present	present	absent
Transition mechanism		niche absorption	niche absorption/ ejection	technology push/ displacement	technology disappearance/ appearance
Phase speed/time	**Pre-development**	slow/long	very slow/very long	fast/short	fast/very long
	Take-off	fast/long	slow/long	fast/short	slow/long
	Acceleration	fast/long	slow/long	fast/short	slow/long
	Stabilisation	slow/long	slow/ very long	slow/short	slow/long
Degree of change		modular	architectural	architectural	architectural
Changes involved		incremental-modular	modular-radical-architectural	radical-architectural	architectural
Regime revolution	**Incumbent actors' fate after transition**	majority	majority/ minority/ extinction	minority	extinction
	Institutions/ rules changes	moderate	high	very high	new
	Technical variations	moderate	very high	very high	new

Source: Geels & Schot (2007).

A close observation of the pathways reveals that T and S are similar in that both have remains of old technologies after transition. Similarly, R and D/R are also similar because both have the characteristics of eliminating old technologies after transition, giving rise to an entirely new regime. In the same vain, T and R are similar in that both have the characteristics of absorbing niche contents in response to landscape developments, although dynamisms in R are advanced stage of T. Moreover, both T and R do not involve a single emergent dominant technology in the transition process but rather multiple inter-locking technologies in distributed areas intended for a common goal. Similarly, D/R and S exhibit similarities in that transition in both cases are centred on the emergence of a single dominant technology in regime throughout the transition process. In addition, R and S also exhibit similarities because in both cases, an old technology is being displaced and replaced by new ones, although R involves multiple technology emergences and S involves a single technology emergence. However, each pathway has a unique feature that may not be comparable to any of the other pathways.

The similarities among the pathways give rise to a web-like diagram which may be represented as shown in Figure 4.1. The difference between D/R and S is that potential dominant RTs in D/R face emergence competition from alternatives at niche levels and attain a freedom of growth at regime levels resulting from the absence of incumbent regime competitors whereas in S, the reverse is the case; a competition from an incumbent regime during growth and a freedom of emergence from the absence of niche counterparts at niche level. In other words, D/R has an initial transition resistance (during pre-development and take-off phases) and a later transition freedom (during acceleration phase), whereas S has an initial transition freedom and a later resistance.

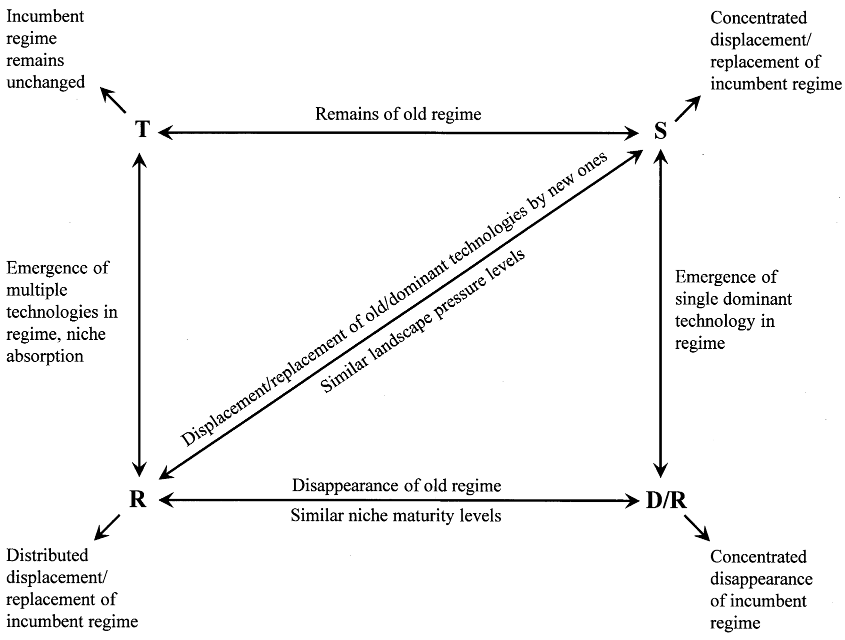


Figure 4.1. Similarity diagram for the transition pathways (Based on Geels & Schot, 2007)

The advantage of fast/short acceleration phase in D/R as a result of low transition resistance arising from incumbent regime disappearance is attributed to the "unbearable landscape pressure" which precedes niche competitions for dominance, whereas the disadvantage of prolonged pre-development and take-off phases (niche competition) resulting from high transition resistance at niche level is a result of the lack of a fully matured niche technology that can guide a timely investment direction. On the other hand, the fast/short pre-development and take-off advantage in S due to low resistance at niche level is a result of the existence of a fully matured NT free of competition, which precedes landscape pressure, whereas the relatively slow acceleration disadvantage due to high resistance is a result of entrenched regime incumbents during NT growth. It may be said that D/R is equivalent to S plus niche competition minus regime competition or S is equivalent to D/R minus niche competition plus regime competition. The table above summarises the relative characteristics of the transition pathways.

4.1.2 Graphical illustration of the transition pathways

Transitions are usually initiated by the impact of disruptive landscape pressures on regime (Genus & Coles, 2008). The development of this pressure reaches a point where the regime can no longer bear its normal activities and begins response to the landscape. Niche level contents are adopted by the regime under the continued action of the landscape to solve perceived problems. The transition (and usually also the landscape pressure) ends when the social and technical components of the new socio-technical regime stabilise together. We therefore distinguish two phases of landscape pressure development; the first phase with a static effect on transition, occurring before transition starts (the static landscape pressure) and the second phase with a dynamic effect on transition, occurring during the transition process (the dynamic landscape pressure). The maximum point of the static landscape pressure (P_{Ls}) or the minimum point of the dynamic landscape pressure (P_{Ld}) marks the starting point of transitions. The landscape pressure that marks the beginning of transitions may also be referred to as the transition landscape pressure (P_{Lt}).

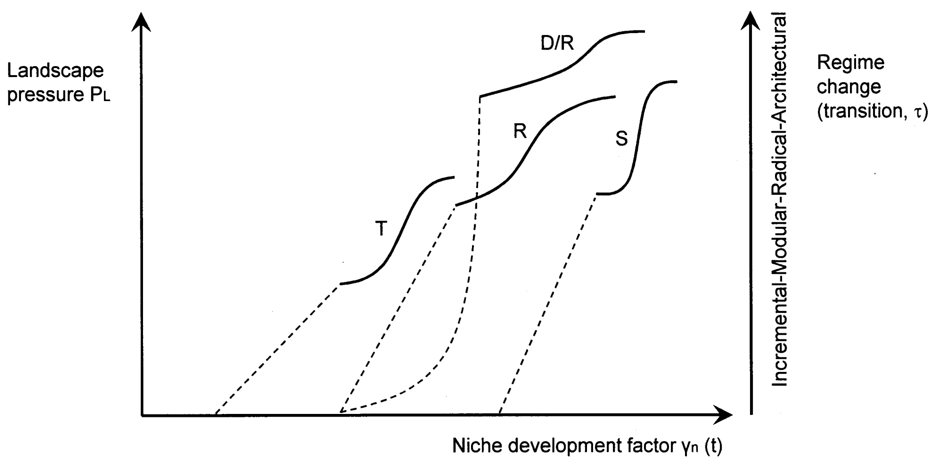


Figure 4.2. Graphical illustrations of transition pathways (Based on Geels & Scots, 2007)

As illustrated on Figure 4.2, the vertical axis on the left represents landscape pressure development P_L, the horizontal axis represents niche development factors in terms of the performance-cost ratios which is a function of time $\gamma_n(t)$, and the vertical axis on the right is for regime changes, i.e. transition τ. Regime change starts from incremental, through modular and radical, and finally ends with architectural change. Also, the dashed and solid lines represent the static pressure (P_{Ls}) and the dynamic pressure (P_{Ld}) respectively. The magnitude and intensity (with respect to time) of these pressures is represented by the height (P_L) and slope (P_L/γ_n) of the pathways respectively. The values for the magnitude and intensity (for both static and dynamic landscape pressure) differ among the various pathways. In addition, the starting point of each pathway relates the maximum P_{Ls} or the transition pressure P_{Lt} to a value of γ_n in accordance with the literature. Since transitions start at P_{Lt}, assuming a linear relationship between technology development γ_n and time *t*, then the various pathways and their phases will be as shown in Figure 4.2 above.

The transformation pathway T is characterised by moderate and gentle landscape pressures P_L (both static and dynamic) on regime and starting at a time (t) when the niche technology (NT) development factor γ_n is low. The pressures for T starting at an early value of γ_n, are also gentle as the slope P_L/γ_n is low, while the transition pressure P_{Lt} is moderate. All the phases involved in this pathway extend considerably over a period (t) of niche innovation process. This is because the multiple niche contents only develop (and are subsequently absorbed by regime) over time ($\gamma_n(t)$). Because both P_{Lt} and γ_n are relatively low, transitions in T end with a modular change (τ axis), leaving the basic architecture of the regime unchanged. A similar pattern may be observed from the reconfiguration pathway R which also extends over a considerable niche development period, although starting at a later stage of γ_n factor with a higher P_{Lt}. It also extends over a wider and higher maturity phase of NT development period compared to T. Both the static and dynamic pressures (P_{Ls} and P_{Ld}) for R are higher and also steeper than in T, making transitions in R an architectural change.

For the de-alignment/re-alignment pathway D/R, the static pressure P_{Ls} starts at a moderate value of γ_n and grows gradually in the beginning and suddenly escalating to a very high value within a short time, attaining P_{Lt} (at similar γ_n to R) with a highly disruptive effect on regime. Transition is triggered, the regime crumbles and the prolonged pre-development and take-off phases in D/R cover a long range of $\gamma_n(t)$ axis as indicated. Although dynamic pressures in D/R are not too high, the transitions end with architectural changes because of the enormous effect of P_{Lt} which erodes the regime, giving way to entirely new one. Finally, the static pressure P_{Ls} in S starting at a high value of γ_n grows rapidly to its peak at P_{Lt} to trigger a transition. The dynamic pressure period (or transition period) for this pathway is relatively short because NTs are already fully developed. Thus the pathway S does not extend over a long range of γ_n and transition processes are relatively fast, driving the regime change to an architectural change.

4.1.3 Limitations of the graph

- The assumption that niche technology development is linear with time might not always be true, especially when there is a technology breakthrough.
- The starting points of the pathways in relation to the transition axis (τ axis) give the impression that the pathways start at a time when regime changes have occurred, and thus should be neglected.
- The changing slopes and the stabilisation phase pressures of the pathways do not give accurate relationships with the P_L axis and thus should only relate to the τ axis.

4.2 Possible pathway sequence

Transitions may involve one or more of their pathways which may be occurring at different or same times. For a transition that is distributed in more than one societal sector level (a multi-sector level transition), it is possible to have different sectors undergoing same or different pathways at a given time. It is even possible to have a coincidence of starting points of pathways among the different sectors. The concurrent pathways among the different sector levels are likely to be the same where the percent sector contributions in landscape development do not differ significantly, otherwise they are likely to be different. In this case, there is less interdependence of the existence and interactions of pathways among the various sector levels. However, this might not be the case when the transition is viewed from a single level or with transitions that involve only one sector level, because pathway emergence in this case are more interdependent. Therefore, where all the pathways are involved, uni-sector level transitions better reveal the possible sequence of pathway emergence whereas multi-sector level transitions have a higher tendency to combine more pathways and are more independent because of the broader transition scene.

Although transitions in both the cases may not have to involve all the four pathways and exhibit some pathway independence, a possible sequence may be defined in terms of the values of P_L and γ_n such that the occurrence of a particular pathway for a transition becomes a measure of the seriousness of a situation and progress in the desired direction. This implies that a higher scenario in the sequence means a further and closer step to the object of transition in a more serious situation than a lower scenario. Based on Geels and Schots (2007), progressive landscape development first attains the transition pressure (P_{Lt}) level of the transformation (T), through the reconfiguration (R) and substitution (S) and finally de-alignment/re-alignment (D/R), i.e.;

$$P_{Lt.T} < P_{Lt.R} < P_{Lt.S} < P_{Lt.D/R}$$

For the corresponding NT development factor γ_n, the sequence begins with T, through R or D/R, and finally S, i.e.;

$$\gamma_{n.T} < \gamma_{n.R} / \gamma_{n.D/R} < \gamma_{n.S}$$

Except for S with $\gamma_n \geq 1.0$, the starting niche development levels for all the other pathways are such that $\gamma_n < 1.0$.

It is clear that R is next to T both in P_{Lt} and γ_n levels but what is not clear is the next superior scenario to R. S is closer to R in the P_{Lt} direction whereas D/R is closer to R in the $\gamma_n(t)$ direction. Therefore, the sequential pathway ranking in the direction of landscape pressure will be in the sequence T-R-S-D/R, whereas in the direction of niche maturity levels, the sequence will be T-R-D/R-S. The next stage will be to compare the P_{Lt} gap of D/R to R ($P_{Lt.D/R} - P_{Lt.R}$) and the γ_n gap of S to R ($\gamma_{n.S} - \gamma_{n.R}$) as well as the rates of change of P_L and γ_n. This is because a developing phenomenon involving a fast speed or a short distance precedes one with a slow speed or a long distance. In transitions therefore (assuming equivalent differences for $P_{Lt.D/R} - P_{Lt.R}$ and $\gamma_{n.S} - \gamma_{n.R}$), when niche development is relatively faster than landscape development from R, the pathway sequence T-R-S-D/R becomes more likely whereas a faster landscape development than niche favours the sequence T-R-D/R-S. In the same vain (assuming equivalent rates of change of P_L and γ_n), when the $P_{Lt.D/R} - P_{Lt.R}$ difference is wider than $\gamma_{n.S} - \gamma_{n.R}$, T-R-S-D/R is more likely and when $P_{Lt.D/R} - P_{Lt.R}$ difference is shorter than $\gamma_{n.S} - \gamma_{n.R}$, T-R-D/R-S is more likely. Therefore, in the case of equivalent P_{Lt} differences and P_L and γ_n change rates, then beyond *a*, an intermediate scenario *X* for D/R and S may be observed (Figure 4.3).

The minimum value for *X* will be at *a* while the maximum value will be at *b* where $P_{Lt.D/R}$ and $\gamma_{n.S}$ have been attained. Triangles R-D/R-S and *b*-D/R-S will be isosceles and the slope P_L/γ_n at any point along line R – *b* is constant. In this scenario, part characteristics for both D/R and S begin to emerge. The resultant effect of *X* on a regime may be an incomplete de-alignment of an incumbent dominant technology resulting from the high P_{Lt} alongside the emergence of near-fully developed alternative(s). If only one single NT attains the development level in *X*, resistance in emerging as dominant will be lower than S because of the partial space created by the shrinking dominant regime due to P_{Lt} enormity. If multiple NTs attain the development level in *X*, the result will be the emergence of near-fully developed niche alternatives. In the race for the dominant position, the emergence resistance will still be lower and less intense than in D/R because of the high confidence and low uncertainty in investment among all the alternatives. The dominant position is instantly occupied giving rise to a dominant regime practice alongside other strong alternatives.

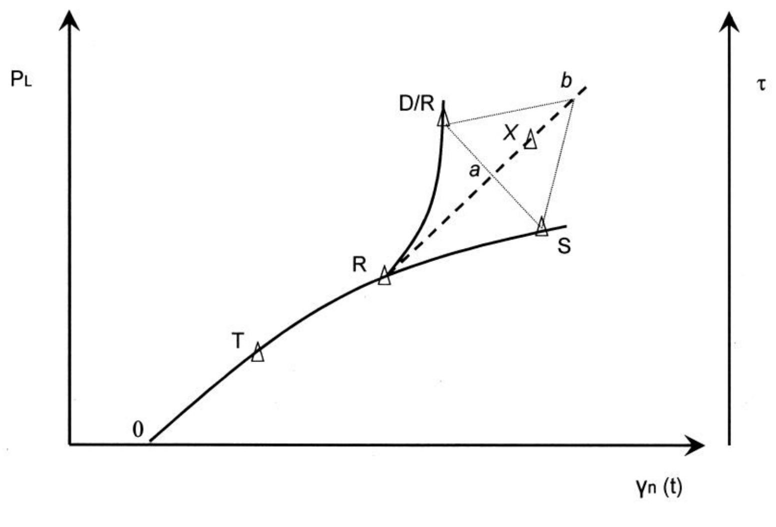


Figure 4.3. Alternate sequence of transition pathways

Again two conditions might be identified; whether the strong alternatives have become part of the regime or are confined to the niche level owing to the high acceptability of the dominant practice. In the former case, the regime will be more or less stable because of the already defined regime settings. In the later case however, in view of the availability of strong niche elements, there is every tendency that the new dominant regime might not maintain this position for a long time that another niche replaces it. Eventually, we will have an unstable substitution pathway with a partly de-aligned regime involving what looks like competing niches. Therefore in addition to the magnitude of external development and the niche maturity level, determinants in scenario *X* also include the number of emerging niches with the upsurge of landscape development.

Consequently, *X* involves both S and D/R characteristics in that substitution is involved although unstable, and a high disruptive pressure and de-alignment is also involved although partial, in association with competing technologies although at different niche/regime levels. Furthermore, it is not S because the incomplete downfall of incumbent regime is not attributable to ‘technology push’ (absence of its transition mechanism) and also the instability of new regimes in view of the seemingly competing technologies, neither is it a D/R because of the inadequate disruptive pressure, incomplete disappearance of incumbent regimes, and a relatively fast emergence of a dominant option. Finally at *b*, complete regime de-alignment and full NT maturity levels are expected which further eases the transition process in terms of low investment uncertainties and absence of an entrenched regime.

However, due to possible deviations from these assumptions in theory, triangles R-D/R-S and *b*-D/R-S might not be isosceles and between R and *b*, the slope P_L/γ_n will not be constant (it will deviate from line R – *b*). This implies that *X* could be located anywhere within the region *b*-D/R-S, but the location of *X* (determined by the coordinates of P_L and $\gamma_n(t)$) and the rate of change of P_L with respect to γ_n (determined by the slope $\delta P_L/\delta\gamma_n$ at *X*) determine the status of the scenario in terms of D/R and S. In general, scenario *X* is more of D/R if its location is in the region *b*-D/R-*a* or is D/R biased when the slope $\delta P_L/\delta\gamma_n$ at *X* is greater than that for R – *b* and is more of S if its location is in the region *b*-S-*a* or is S biased when the slope $\delta P_L/\delta\gamma_n$ at *X* is less than that for R – *b*.

4.2.1 Effect of pathway history on P_L development and sequence

The rate of change of P_L in turn depends on the pathway history of a transition. For a specific transition, the occurrence of a transition pathway tends to decrease or eliminate the negative consequence of landscape developments, thereby prolonging growth time of landscape pressures and extending the need for another transition (and hence pathway). Therefore, a transition that witnessed more pathways before D/R and S would have a lower P_L change rate or time intensity than one that has not and the slope $P_L/\gamma_n(t)$ beyond R decreases in favour of T-R-S-D/R. Consider a landscape development that rises to $P_{Lt.T}$ to cause transformation pathway (T). As shown in Figure 4.4, the action of T decreases this pressure by $-P'_{L.T}$ to a lower value of $P''_{L.T}$ (such that $0 \leq P''_{L.T} < P_{Lt.T}$) and therefore the leftover landscape pressure at T, would be;

$$P''_{L.T} = P_{Lt.T} - P'_{L.T} \qquad (4.1)$$

This means that $P_{Lt.T}$ has been cut down to $P''_{L.T}$ by T which needs additional landscape pressure development (and hence time) say P_{Lx} to rise to $P_{Lt.R}$, i.e. $P''_{L.T} + P_{Lx} = P_{Lt.R}$ and hence;

$$P''_{L.T} = P_{Lt.R} - P_{Lx} \qquad (4.2)$$

Solving for P_{Lx} by equating equations (4.1) & (4.2) gives;

$$P_{Lx} = |P'_{L.T}| + (P_{Lt.R} - P_{Lt.T}) \qquad (4.3)$$

(which implies that $P_{Lx} > P_{Lt.R} - P_{Lt.T}$).

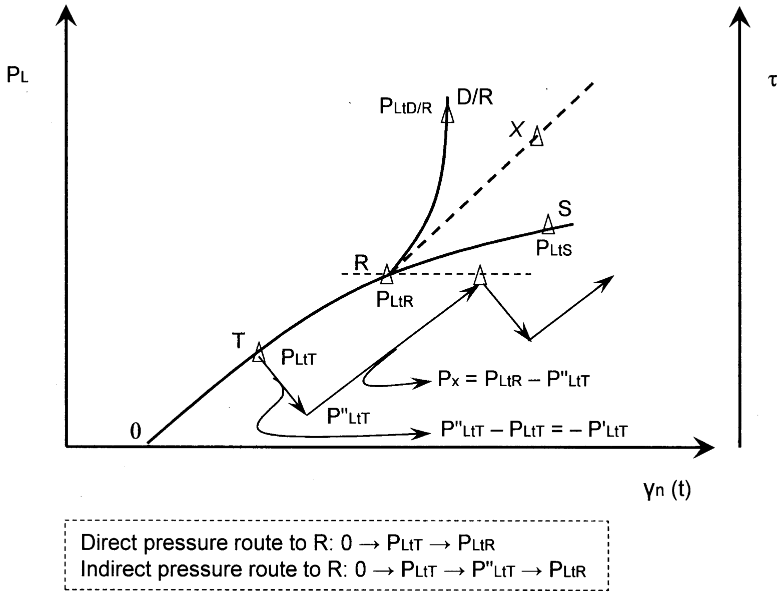


Figure 4.4. Effect of transition pathway history on P_L intensity

Let the corresponding times required by $P_{Lt.T}$, $P'_{L.T}$, $P''_{L.T}$, P_{Lx} and $P_{Lt.R}$ be t_{T1}, t_{T2}, t_{T3}, t_x and t_R respectively. Then the indirect route of pressures to R through T will be $0 \rightarrow P_{Lt.T} \rightarrow P''_{L.T} \rightarrow P_{Lt.R}$ while the summation of the corresponding pressure changes involved will be;

$$P_{Lsum.ind} = P_{Ls.T} - P'_{L.T} + P_{Lx} \qquad (4.4)$$

And the summation of the corresponding times is;

$$t_{sum.ind} = t_{T1} + t_{T2} + t_x \qquad (4.5)$$

The direct pressure route to R, is $0 \rightarrow P_{Lt.T} \rightarrow P_{Lt.R}$ while the corresponding pressure change summation is $P_{Ls.T} + (P_{Ls.R} - P_{Ls.T}) = P_{Ls.R}$, therefore;

$$P_{Lsum.dir} = P_{Ls.R} \qquad (4.6)$$

And its corresponding time is;

$$t_{sum.dir} = t_R \qquad (4.7)$$

By substituting eq. (3) into (4), the indirect route pressure sum will be;

$P_{Lsum.ind} = P_{Ls.T} - P'_{L.T} + P_{Lx} = P_{Ls.T} - P'_{L.T} + [P'_{L.T} + (P_{Ls.R} - P_{Ls.T})] = P_{Ls.R}$, (recall eq. 4.6) then;

$$P_{Lsum.dir} = P_{Lsum.ind} \qquad (4.8)$$

Since $P_{Lt.R} = P_{Lt.T} + (P_{Lt.R} – P_{Lt.T})$ and $P_{Lx} > P_{Lt.R} – P_{Lt.T}$, then $|P_{Lt.R}| < |P_{Lt.T}| + |P'_{L.T}| + |P_{Lx}|$ and hence for $P_{Lt.R}$ development through the different routes, $t_R < t_{T1}+ t_{T2}+ t_x$, (recall eq. 4.7 & 4.5) then;

$$t_{sum.dir} < t_{sum.ind} \tag{4.9}$$

Although in both cases of the direct and indirect routes to R, the final common pressure is $P_{Lt.R}$ (eq. (4.8)), the respective time periods t_R and $t_{T1}+ t_{T2}+ t_x$ are such that $t_R < t_{T1}+ t_{T2}+ t_x$. Therefore, the time intensity of $P_{Lt.R}$ through the two routes will differ:

For the direct route (without T action), the intensity will be $P_{Lsum.dir}/ t_{sum.dir}$, i.e.;

$$P_{Lt.R}/t_R \tag{4.10}$$

Whereas for the indirect route (with T), the intensity will be $P_{Lsum.ind}/t_{sum.ind}$;

$$P_{Lt.R}/t_{T1}+ t_{T2}+ t_x \tag{4.11}$$

The fact that $t_R < t_{T1}+ t_{T2}+ t_x$ indicates that $P_{Lt.R}$ is spread over a longer time period with the action of T and obviously the pressure intensities will differ such that;

$$P_{Lt.R}/(t_{T1}+ t_{T2}+ t_x) < P_{Lt.R}/t_R \tag{4.12}$$

Equation (4.12) means that the intensity of $P_{Lt.R}$ is reduced with the action of T; a previous pathway to R.

A similar observation can be deduced from the action of R on a next pathway. This means that in a transition, the rate of change of landscape pressure or the time intensity of P_L, i.e. P_L/t decreases with the actions of preceding pathways (along the sequence) due to increase in P_L growth period. And since niche maturity level γ_n is more or less linear with time, $P_L/\gamma_n(t)$ also decreases for the same reason. Generally, a transition that involves more of T and/or R at the early right stage of its landscape development is more inclined towards -S-D/R sequence than one that has not.

4.2.2 Effect of transition policy on γ_n development and sequence

Normative niche innovations and system improvements under reproduction pathways are accelerated by pressures from landscape and regime levels, just as promotions of incumbent regime technologies are challenged (and eventually decelerated) by landscape pressures. Under a disruptive landscape pressure, policy settings on specific regime practices affect the continuity and scale of their adoption. Stricter regulations and taxes on regime technologies (RTs) for instance have negative effect on their overall cost-performance factors γ_r, whereas dedicated research, development and deployment efforts and learning processes through funding, incentives and subsidies on niche technologies (NTs) improve their overall cost-performance factor γ_n (Figure 4.5).

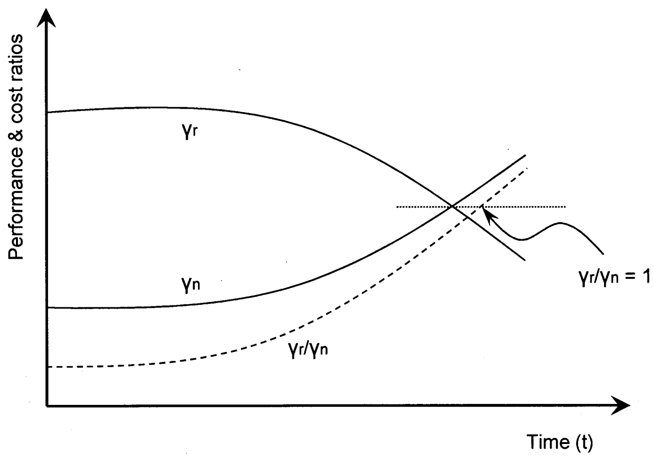


Figure 4.5. Effect of transition policy on γ_n development & adoption

Overtime time therefore, infrastructure innovation and investment gradually shift towards NT development, leading to a competition between NTs and RTs. This implies that the relative performance-cost ratio of NTs in relation to RTs, γ_n/γ_r which is a function of time t, (γ_n/γ_r (t)) in a transition economy grows overtime (Figure 4.5).

4.3 Conclusion

This chapter has provided a simplified analysis and presentation of transition pathways with the aim to open the black-box of the possible pathway sequences. The pathways exhibit a ranking of succession in which the transformation pathway (T) is first in the sequence in terms of both landscape pressure (P_L) and niche maturity levels (γ_n). The next pathway along the sequence in terms of the two variables of P_L and γ_n is the reconfiguration pathway (R). Beyond R, there is not much certainty about the next pathway because the substitution pathway (S) is significantly higher in terms of γ_n whereas the de-alignment/re-alignment pathway (D/R) is significantly higher in terms of P_L. Therefore, the next pathway to R on the sequence will depend on the difference in the rates of change of P_L and γ_n (i.e. $P_L/t - \gamma_n/t$) for a transition and also the P_L difference of R to D/R ($P_{L.D/R} - P_{L.R}$) and the γ_n difference of R to S ($\gamma_{n.S} - \gamma_{n.R}$). A higher $P_L/t - \gamma_n/t$ and/or a smaller $P_{L.D/R} - P_{L.R}$ than $\gamma_{n.S} - \gamma_{n.R}$ support the sequence of T-R-D/R-S whereas a lower $P_L/t - \gamma_n/t$ and/or a larger $P_{L.D/R} - P_{L.R}$ than $\gamma_{n.S} - \gamma_{n.R}$ is more towards T-R-S-D/R sequence. In the case of equivalent $P_{L.D/R} - P_{L.R}$ and $\gamma_{n.S} - \gamma_{n.R}$, and also P_L/t and γ_n/t, then sufficiently beyond R, a fifth scenario (*X*) which combines part characteristics of both D/R and S has been discussed. In view of possible deviations from this assumption in theory, changes in P_L and γ_n (and hence *X*) might not be equivalent and is determined by the slope $\delta P_L/\delta\gamma_n$ while the status of *X* with respect to D/R and S at any time depends on its parametric proximity with respect to D/R and S at that time. However, in all cases, there is the need to establish accurate measurements for P_L and γ_n and identify their precise values in each of the pathways to enhance the certainty of the pathway sequence.

CHAPTER 5

TRANSITION PATHWAYS IN THE UK ROAD TRANSPORT SECTOR

5.1 Introduction

The current road transport sector in the UK is dominated by fossil fuel internal combustion engine (ICE) vehicle regime and is faced with several tensions resulting from oil crises, neo-liberal policies and climate change, which affect the sustainability fate of fossil fuel-dominated systems (Shackley & Green, 2006; Bird, 2007; Høj, Kato, & Pilat, 1995; Jesse & Linde 2008; Department of Energy and Climate Change [DECC], 2012c; King & Gulledge, 2013). As the UK road transport sector is a major contributor of domestic GHG (UNFCCC, 2014c), reducing emissions from the road sector can play a significant role in actualising the nation's targets formalised in the 2008 climate change act (CCC, 2014). Various low carbon strategies have been deployed to meet the nation's emissions reduction ambitions while maintaining other objectives of energy security, reliability and affordability. In a similar response at the regional level, the European Commission sets various mandates and targets to actualise the low carbon transition burdens of its member states (European Commission, 2014). Policies and strategies to meet these goals are based on efficiency improvements of conventional vehicles as well as the uptake of ultra-low emission vehicle (ULEV) technologies.

The political, economic and environmental challenges faced by the UK road transport sector can be clearly understood when using the multi-level perspective (MLP) framework to assess landscape pressure developments. These pressures include macro-economic policies such as privatisation, de-regulation and market liberalisation, and macro-economic trends like oil price volatility, supply disruptions, resource depletion and environmental issues including climate change (Shackley & Green, 2006; Geels, 2011). The low carbon transport technologies that have not yet replaced the existing fossil fuel vehicle regime from the dominant position exist at the niche level of the MLP. Transitions usually follow certain dynamic pathways resulting from multi-level interactions between the three levels; namely, landscape, regime and niche levels (Schot & Geels, 2008). Therefore, such socio-technical dynamics can help to reveal the present and possible future states of the current developments in UK road transport sector.

The aims of this chapter are to use the multi-level and multi-phase perspectives:

1) To analyse the current transition dynamics in the UK road transport in terms of socio-technical transition pathways;

2) To identify existing pathways, their current status and likely future pathways; and

3) To discover the pathway(s) necessary for full decarbonisation in the road sector.

Special care has been taken in gathering data and information from literature. If the quality of data/information appeared to be compromised for any reason, it is thoroughly assessed against other reliable sources to verify their accuracy and validity before adoption. The chapter relates mainly to automotive engine vehicles and may excludes pedal cycles.

5.2 Types of innovations in road transport systems

5.2.1 Types of road vehicle technologies

A number of different types of vehicles are used for road transport. These include cars and taxis, light vans, buses and coaches, heavy goods vehicles, and mopeds and motorcycles (Department for Transport [DfT], 2013). These belong to one or more of the vehicle technologies shown in Table 5.1.

Table 5.1. Types of road vehicle technologies

Technology	Fuel type	Description
ICEVs	Petrol ICE	ICE fuelled by petroleum
	Natural gas ICE	ICE fuelled by natural gas
	Hydrogen ICE	ICE fuelled by gaseous hydrogen
	Synth ICE	ICE fuelled by synthetic fuel (CTL, GTL, or BTL)
FCVs	Petrol FCV	FCV fuelled by petroleum
	Hydrogen FCV	FCV fuelled by gaseous hydrogen
	Synth FCV	FCV fuelled by synthetic fuel (CTL, GTL, or BTL)
EVs	Conventional HEV	Electric vehicle run by ICE and electricity from on-board battery charged by regenerative breaking
	PHEV	Electric vehicle run by ICE and electricity from on-board battery charged externally
	BEV	Electric vehicle run purely by electricity from on-board battery charged externally
	FCEV	Electric vehicle run purely by electricity from hydrogen fuel cell

Source: Grahn et al. (2009); Goldman (2014).

5.2.2 Strategies for low carbon vehicle development

In order to enhance fuel efficiency and reduce emissions, many measures and strategies are set to move the road transport system toward low emission technologies. The first strategy is modifications to conventional technologies of petrol and diesel ICE, which include fuel hybridisation and the invention of vehicles, which are light in weight, aerodynamic in shape and those that use start-stop systems (IEA, 2012). The second strategy concerns the adoption of radically different vehicle technologies with alternative fuels such as battery electric vehicle (BEV) and fuel cell vehicle (FCV). The internal modifications combined with the uptake of ULEVs are the two options for cutting emissions from the road transport sector.

5.3 The UK road transport regime and the landscape pressure acting on it

The road transport regime consists of dominant practices involved in three main areas; production, supply/distribution (networks/markets/infrastructure) and use of fuels and vehicles. The three levels of activities are interdependent, each consists of a diverse range of actors, technologies and rules, and are all embedded within institutions and infrastructure (Geels, 2004). The UK road transport services are met through such regime elements dominated by the production, supply and use of gasoline and diesel fuels and ICE vehicles

(Office for low emission vehicles, 2013). Therefore, the regime in the UK road transport concern tangible and measurable elements (e.g. ICE vehicles, fossil fuels, infrastructure, regulations, public opinion, skills, etc.) as well as non-tangible elements (e.g. shared beliefs, norms, heuristics, etc.) (Geels, 2012). The philosophy behind regime is that actor behaviour is constrained and regulated at the regime level, making individual elements relatively autonomous (Geels, 2004). This gives the UK road transport regime stability as actor behaviour at the micro-level is not easily changed.

The regime at the collective is stable because of lock-in mechanisms of shared beliefs and consumer lifestyles, rules and regulations, sunk investments by key players in infrastructure, human resource, equipment, technical complementarity, affordable prices due to economies of scale, that create barriers for new market entrants (FarmPath, 2014). These interdependent forces gives the present fossil fuel based road transport regime a strong inertia and is responsible for its perpetuation despite its environmental and energy security consequence (Unruh, 2000). The current road transport sector in the UK suffers from a number of problems existing as the landscape pressure. These include the negative effects of climate change due to emissions of GHGs, local air pollutions, government (national, European and global) commitments to meet targets for carbon emissions reductions (through the promotion of cleaner energy sources), issues around security of primary energy supplies, concerns over high oil and gas prices, depletion of resources and commitments to neo-liberal policies in energy markets (European Commission, 2001; Foxon, Hammond, & Pearson, 2010).

5.4 Low carbon transition pathways in road transport

The previous section discusses the literature on socio-technical transition pathways in its original form. This section deals with how this literature applies to low carbon transition in road transport system.

5.4.1 Transformation in low carbon road transport

At moderate pressure resulting from climate change and energy security issues, policies will begin to emerge at the national, regional and/or global levels on targets to limit carbon emissions from a fossil fuel regime road sector. This pressure may be interpreted as increasing criticisms from environmental pressure groups and social movements encourage existing actors to adjust their development focus towards more fuel efficient conventional and carbon-free vehicles (Verbong & Geels, 2010). Since the pressure is moderate, the guiding principles of actors (government, firms, users, etc.) will be modest and are mainly market-based. The result will be a modest restructuring of institutions and technologies as actors have the impression that moderate improvements and/or investments in transport infrastructure will address the challenge.

Legislation from government actors emphasises investments in low carbon vehicles and also the use of carbon information of vehicles such as colour codes to indicate their carbon intensity in order to influence choice. Vehicle production actors modify existing vehicle technologies of ICEs to run on blends of fossil fuels and biofuels. Other strategies may include engine friction reduction, weight reduction, low rolling resistance tyres, start-stop system, variable valve control system and more adoption of diesel fuel to improve fuel efficiency (McKinsey & Company, 2009; Society of Motor Manufacturers and Traders [SMMT], 2013). Production of radically different technologies of ultra-low carbon vehicles (ULCV) such as BEVs and hydrogen FCVs are also likely to increase. Consumer actors tend to invest in improving carbon and fuel efficiency of conventional vehicles, but may also consider investment in ULCV. But due to the moderate pressure, ULCV are mainly confined to specific niches such as the small size vehicle niche, high income class niche and the built environment. Conventional ICE vehicles may be modified to run on fossil fuel blends, constructed from lighter materials, take aerodynamic shapes and designed with start-stop systems. Most actors survive under this pathway, but some may disappear through measures or take-overs leading to a moderate change in the social network (Renaud, 2014). This development will drive down the average vehicle emissions without affecting the basic structure of the existing regime.

5.4.2 Reconfiguration in low carbon road transport

High increases in the effects of climate change and energy supply shocks associated with global competition on resources or political instability in oil-rich nations will result to a huge landscape pressure on the existing regime. Such developments put pressure on actors to prioritise reliability over profitability. Actors will not only prioritise fuel efficiency more than before, but also production will focus on a substantial deployment of alternatively-fuelled vehicles. There will be more cooperation at the regional level and among individual firms in tackling carbon emissions and energy insecurity (Tyler, 2011). Regional regulations will dominate efforts in a shift to sustainable energy. Government actors will consider stricter regulative policies for restructuring the transport sector toward sustainable pathways. Under such pressures, some transport firms will disappear through merger and acquisition resulting in fewer large companies with international roles (Ferris & Petitt, 2013; Peavler, 2014). The reconfiguration pathway will be characterised by regional policies and markets, as well as fewer but larger firms with suitably-aligned road transport systems.

Restructuring measures toward BEVs as a niche technology may involve the adoption of HEVs in which the fuel is partly electric and partly gasoline/diesel. An increased landscape pressure will trigger the significance of high performance rechargeable batteries such as lithium-ion cells (Pikul et al., 2013). To enhance the service duration of batteries, innovations toward low resistance movements of such vehicles will be crucial. Vehicles that are light in weight and aerodynamic in shape with low resistance tyres are important options. Other innovations are likely to include air conditioning modification and an automatic start-stop system. Increasing the number of electrically-powered vehicles will engender congestion at refuelling station, thus necessitating the innovation of fast and rapid charging point technologies as well as battery switching stations to eliminate long refuelling duration. The increased demand for electricity will require the expansion of electric power capacity (from low carbon sources). Under the reconfiguration pathway for BEV, the road infrastructure will be characterised by fast/rapid recharging points and battery switching stations, as well as a higher capacity of a centralised low carbon electricity generation. Increasing investment in such individual but inter-dependent technologies and the continuous adoption and inter-linkage between the various components will result in the gradual reconfiguration of the basic architecture of the road transport system toward BEV.

The reconfiguration process for hydrogen FCVs is likely to follow similar processes. Under increasing landscape pressure, there will be the need for higher production, transport and storage of hydrogen fuel. Hydrogen production will shift from natural gas to carbon-free production methods such as the electrolysis of water (FuelCellToday, 2013). Other promising technologies for hydrogen fuel production are high heats from next generation nuclear power plants capable of splitting hydrogen from water (Patterson & Park, 2008). Parallel to the hydrogen production technologies are the emergence of various storage and transport technologies. Storage technologies include liquefaction and compression infrastructure to increase its energy density. Another method is the solid-state storage by metal hydride compounds that can trap hydrogen molecules at room temperature and pressure (Wise, 2014). The development of this storage system will induce the need to reconfigure efficient distribution infrastructure. Some of the current materials will need to be replaced with more resistant ones. As a consequence of an increased demand for hydrogen, trucking and railing may become slow and ineffective, increasing the focus on pipeline transport systems. Local (production at the point of use) and on-board (self-production by vehicles) production technologies may be good alternatives to avoid high costs inherent in transporting hydrogen. Reconfiguration of hydrogen FCV will result in a road system regime with hydrogen refuelling stations, industries for the electrolysis of water, local hydrogen production technologies and hydrogen resistant pipelines. The reconfiguration towards biofuel vehicles will follow similar pattern with hydrogen FCVs in terms of production, transport and storage but may require less or no technical changes because of its compatibility with existing fossil fuel infrastructure (European Commission, 2011a; Ogden et al., 2011; Energy Innovation, 2014).

5.4.3 Substitution in low carbon road transport

During high effects of climate change (global warming) and fossil resource supply insecurity, the incumbent fossil fuel vehicle regimes will face enormous challenges leading to tighter settings of emission regulations. The current fossil fuel transport industry is likely to become unstable in terms of sustainability, creating windows of opportunity for alternative low carbon vehicles. Policies and programmes will be focused toward alternatively fuelled vehicles. At this point, when any of the radical innovations in electric, biofuel or hydrogen vehicle technologies is fully matured at the niche level, conditions in the existing fossil fuel regime are favourable for its suitable penetration and can smoothly replace it. This can occur in relatively short time, because market conditions are favourable for their adoption. A substitution associated with electric vehicles will have the implication of an increase in electricity generation capacity from low carbon sources (to avoid ‘carbon leakage’) in view of investment in electric vehicles.

5.4.4 De-alignment/re-alignment in low carbon road transport

When oil supply security becomes highly uncertain for whatever reason and/or the effect of climate change results in high global temperatures causing relatively severe, long-duration and more frequent floods and storms among others, the landscape pressure becomes unbearable. Under such huge pressures, actors may lose fate in usual solutions, resulting in the (possible complete) termination of the dominant petrol and diesel vehicle industry. National and regional government will direct policies toward reviving other alternative fuel vehicles (AFVs).

The guiding principle under this pathway is pre-dominantly a strong preference for local fuel production and the use of sustainable transport options. Incumbent fossil fuel vehicle producers will seize to exist, giving way to the emergence of numerous experimentations in low carbon vehicle industry. These experiments are largely undertaken by a new network of actors in various niches such as the taxi-niche, luxury-niche and racing-niche. Most ULCV technologies such as electric and biofuel vehicles will dominate the transport sector with independent ownership under various niches. These technologies will co-exist for a considerably long period due to uncertainty in a reliable investment options. There will be no clear substitute to the defunct regime and the transport industry will be characterised with a combination of a variety of potential alternatives. Eventually, one option will emerge dominant in the long-run. This pathway will be initially characterised by early and wide adoption of AFVs across all types found both within and outside the built environment, and later on by a single dominant adoption (Geels & Schot, 2007).

5.5 The development of landscape pressure on UK road transport

The two most important landscape pressures acting on fossil fuel regimes are the global average temperature (GAT) anomalies (relative to 1980-1999) and the energy security issues

(ESI). GAT is a function of GHG emissions since the post-industrial era with consequent changes in the earth's climate system whereas energy insecurity is a function of global fossil fuel price fluctuations due to high demands and/or supply disruption for social or political reasons, typical of which is the 1970s oil crises. These developments have continued to make alarming impact on a full reliance on fossil fuel as energy sources (IPCC, 1990; Bird, 2007; Oberndorfer, 2009; DECC, 2012c).

The IPCC's first (1990), second (1995), third (2001), fourth (2007) and fifth (2014) assessment reports provided likely global mean temperature (GAT) changes by year 2100 based on prevailing conditions at the time of the assessments. The respective likely temperature changes relative to 1980-1999 GAT from its reports are 5.96, 2.25, 3.6, 4 and 3.275 degrees Celsius. The consequence of this finding created fear among countries across the world leading to the formulation of legally binding commitment under the Kyoto Protocol which sets mandatory targets on ghg emissions for the world's leading economies including the UK. Having perceived this negative development as a disruptive pressure at the landscape level which led to the unanimous adoption of the protocol in 1997 and its entrance into force in 2005, the EU/UK came up with various action plans on how to mitigate harmful emissions from road transport (UNFCCC, 2014e).

In 2007, the EU climate change legislation set binding targets for regulating emissions from road vehicles through reductions in carbon emission rates and promoting fuel efficiency. For cars, the EU enforced a fleet average emission target of 130 g carbon dioxide per km by 2015 and 95 g carbon dioxide per km by 2021. This is set against the 2007 fleet average of 158.7 g carbon dioxide per km. For fuel consumption, the target is set at 5.6 litres per 100 km of petrol or 4.9 litres per 100 km of diesel by 2015, and around 4.1 litres per 100 km of petrol or 3.6 litres per 100 km of diesel by 2021 (European Commission, 2014); Smokers et al. 2010;

International Council on Clean Transportation 2014). Table 5.2 summarises the EU's road sector emission targets. For heavy-duty vehicles (HDVs), no regulation has been effective so far but a short-term strategy focuses on measurement and reporting HDV emissions.

Also, the 2009 European renewable energy directive requires that 10% of transport fuel should be sourced from renewables, while the European fuel quality directive requires at least 6% reduction of emission intensity of fuels used in vehicles by 2020. Emission targets are monitored and encouraged by the EU through various strategies such as payments of penalties for non-compliance, incentives through eco-innovation credits, super credits, and providing the right environment for smaller manufacturers. Others measures include labelling, which carries carbon efficiency information of vehicles indicating their emission intensities and fuel consumption rates (European Commission, 2012, 2014).

Table 5.2. Emission reduction targets for new vehicles in the EU

Vehicle class	Rates	Fleet average	Targets	Phase in period
Cars	Emissions (g CO_2/km): 2007 fleet average	158.7 g CO_2/km	130 g CO_2/km by 2015	2012 to 2015
			95 g CO_2/km by 2021	2020 to 2021
	Fuel (litres/100km)		5.6 petrol or 4.9 diesel by 2015	-
			4.1 petrol or 3.6 diesel by 2021	-
Vans	Emissions (gCO_2/km): 2012 fleet average	180.2 g CO_2/km	175 g CO_2/km by 2017	2014 to 2017
			147 g CO_2/km by 2020	2020 to 2020
	Fuel (litres/100km)		7.5 petrol or 6.6 diesel by 2017	-
			6.3 petrol or 5.5 diesel by 2020	-
Heavy-duty vehicles	Emissions (gCO_2/km)		-	-
	Fuel (litres/100km)		-	-

Source: European Commission (2014).

5.6 Pathway analysis for the road transport sector

Using the historical changes in landscape pressure and niche technology maturity levels from year 2000, the MLP can be used to analyse the transition dynamics in the UK road transport. With the landscape development in place since 2000, the MLP analysis is carried out with respect to the roles of the other two levels (socio-technical regime and technological niche) to figure out the status of the low carbon journey in terms of the transition pathways.

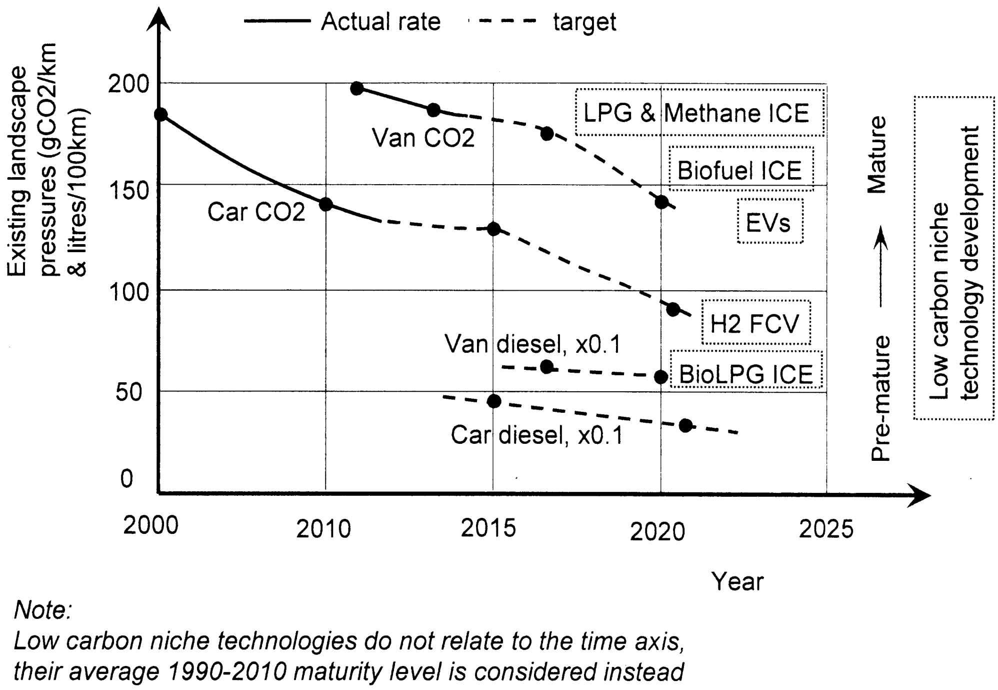


Figure 5.1. Landscape pressure (translated) on UK road transport regime (SMMT, 2014; European Commission, 2011b, 2014)

5.6.1 Low carbon developments in road transport regime

Responding to landscape pressure and the EU emissions regulation, the UK agreed to the EU new car emission regulation in 2008 and shifted focus toward carbon and fuel efficiency improvement of conventional vehicles in the socio-technical regime level and the uptake of ULEVs from the technological niche level (DfT, 2009). These include the use of LPG in ICEs, use of biofuel blends in ICEs through the Renewable Transport Fuel Obligation

(RTFO), and an increasing deployment of battery and hybrid electric vehicles, electric car recharging points through the Bus Service Operators Grant (DfT, 2012; DfT, 2009). Other fiscal measures include fuel duty, company car tax, vehicle excise duty provide price signals to businesses and consumers (DfT, 2009). In order to ensure that the UK is on track, checks are intensified against vehicle CO2 data and about 80.3% of vehicle registration were reported in 1997, which grew to 100% in 2005 (SMMT, 2005). The result shows that the recent years have witnessed a gradual but growing deployment and use of low emission road vehicles and infrastructure in the UK as shown in Figure 5.2.

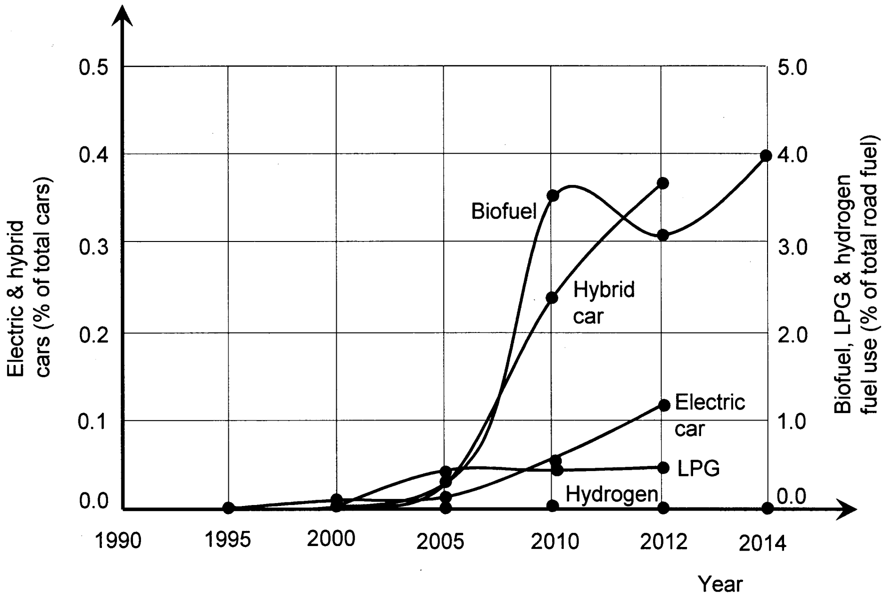


Figure 5.2. Percentage of low carbon development in UK road transport (Centre of Excellence [CENEX], 2014; DfT, 2014; Her Majesty's Revenue and Customs [HMRC], 2014; Factfish, 2014)

5.6.2 The role of the regime in the low carbon development

In the 2000s, the EU/UK perceived the landscape pressure as moderate and believed that minor modifications in vehicle technology for the short and medium term are a good alternative solution (CENEX, 2014; DfT, 2014; HMRC, 2014). National and regional policies were directed toward modifying existing conventional vehicles in the UK road transport regime during which ultra-low emissions vehicles (ULEV) such as BEVs and hydrogen FCVs were not fully matured. Road vehicle manufacturers responded by modifying their conventional technologies toward fuel efficiency and fuel hybridisation. Reorientation of regime elements occurred through growing manufacture of flex-fuel vehicles that use liquid biofuels blends in ICEs as well as HEVs. Regime reorientation also included the production of light weight and aerodynamic vehicles as well as those that use start-stop systems (Next Greencar, 2014a). Vehicle users were motivated to make carbon-efficient vehicle choices through incentives from government, environmental awareness campaigns and the like. In view of the relatively mild impact of pressure from the landscape resulting from IPCC's report and historical experience of supply shocks, the guiding principle for the transition is profit-oriented. Actors perceive investments in large-scale ULEV as too expensive and unnecessary. Under this pathway, the regime basically remained unchanged as the technology and actor network have not been disrupted.

5.6.3 The role of the technological niche in the low carbon development

As the landscape pressure became increasingly challenging as translated by the adoption of the carbon budget system of the 2008 Act, the transition priority began to shift from profit-oriented toward environmental safety and energy security. Higher commitments to ULEV began to emerge along various policy efforts directed toward their deployment through the office for low emission vehicles and the technology strategy board's low carbon vehicles innovation platform. Investment in BEV started from the mid-1990s, but has received more attention and accelerated from 2005 until 2012, reaching about 0.012% of total cars on UK roads (Figure 5.2). This development necessitated the expansion of suitable facilities needed to sustain their functionality, namely batteries and charging points (Next Greencar, 2014b; Element Energy, 2013). Some technology alignment also occurred within these fairly distributed technologies. As slow charging points were considered time-consuming due to the growing number of electric cars, fast and rapid charging points emerged across the UK. Also, the need for high performance batteries triggered the importance of Lithium-ion batteries, which have relatively long service duration (Carbon Descent, 2009). However, this development did not disrupt the regime as such vehicles have been confined to certain niches such as small size vehicle and short distance travel niches (Contestabile, Offer, & North, 2012). Social network of existing actors remain in control of their infrastructure (SMMT, 2013; FreeIndex, 2014).

5.7 Conclusion

This chapter uses the analytical framework of the multi-level and the multi-phase perspectives to explore the low carbon transition pathways for the UK road transport system. The work draws from the impact made by the national (UK) and regional (EU) low carbon policy instruments on the UK road sector. The result shows that the transformation pathway, which is at the take-off phase on a large scale, is the only fully active pathway. The transformation is mainly characterised by the adoption of biofuel blends, hybrid electric vehicles, as well as niche technologies such as battery electric vehicles. For the emergence of an ideal low carbon road system in the UK, it is shown that the transformation pathway is insufficient and the likely pathway sequence to full decarbonisation will be transformation-substitution-de-alignment/re-alignment. However, the dynamics that can favour a smooth process of this sequence will demand a range of active niche technologies and strong government intervention. Thus, key stakeholders such as government, industry, markets and research institutes have a crucial role to play for the success of a fully decarbonised road transport system.

CHAPTER 6

TRANSITION PATHWAYS IN THE UK ELECTRICITY GENERATION SECTOR

6.1 Introduction

Transition to sustainability is a dynamic process which involves the interplay of various forces among multiple actors within multiple domains and at different levels (Loorbach & Rotmans, 2006; Rotmans et al., 2001). The fact that transitions do not come about easily implies that the existing regime is characterised by path-dependency and lock-in (Safarzynska & van den Bergh, 2010; Unruh, 2000). Technical components are embedded and intertwined in a seamless web with infrastructure, institutions and actor skills and expectations (Bolton & Foxon, 2010; Kemp et al., 1998). A socio-technical regime is established by such systemic mechanisms which are responsible for the resistance of the regime to change or to transition to a new alternative. Therefore, for a transition to occur, a (transition) force of certain magnitude needs to act onto the regime to weaken the link holding the socio-technical system (i.e. regime resistance R_r) to cause destabilisation and create opportunities for the adoption of new practices and ultimately change.

Going by the multi-level perspective (MLP) framework (Geels & Schot, 2007), these forces or influences come from both the landscape and niche levels. The landscape level exerts a disruptive pressure P_L on the regime which develops from an external event and/or side effect of the regime (Darnhofer, Sutherland, & Pinto-Correia, 2015; Geels 2011; Patwardhan et al., 2012; A. Smith et al., 2005). Similarly, alternatives at the niche level exert a seductive influence on the regime (technological innovation system) in terms of its relative techno-economic and sustainability performance P_n (Carlsson & Stankiewicz, 1991; Geels, 2011; A. Smith, Voß, & Grin, 2010). Hence, the regime is acted upon by a pushing force on one hand and attractive force on the other. Both forces are important in transitions, however, a transition may occur due to a sole action of an attractive force from niche (technology innovation system) or a combination of P_L and P_n influences. This implies that a transition cannot occur in the complete absence of P_n, no matter how much P_L might develop. Therefore from simple proportional reasoning, it may be said that transition momentum M_t is directly proportional to the influences of landscape pressure P_L and niche performance P_n but inversely proportional to the square of regime (transition) resistance R_r, written mathematically as;

$$M_t \propto \frac{P_n P_L}{R_r^2} = k\,\frac{P_n P_L}{R_r^2} \tag{6.1}$$

The value of M_t determines the status and phase of a transition. The four phases of a transition according to Rotmans et al. (2001) are the pre-development phase, take-off phase, acceleration or breakthrough phase and the stabilisation phase. The values of three quantities P_L, P_n and R_r represent forces and resistance and hence, M_t is a dimensionless measure of the momentum of a transition. Therefore, the regime cracks at $M_t = 1k$ which may also stand for the take-off phase of a transition. The expression $P_L : P_n$ instigates different regime configurations, types and settings of regime policies (Hall, 1993) and determines the type of transition pathway. The four transition pathways according to Geels and Schot (2007) are the transformation, reconfiguration, substitution and de-alignment/re-alignment pathways which result to different regime structuration. When expressed in terms of medium (m), high (h) and extreme (e), the following explanation may be deduced; 1) $mP_L : mP_n$ represent the transformation pathway, 2) $hP_L : mP_n$ represent the reconfiguration pathway, 3) $hP_L : hP_n$ represent the substitution pathway, 4) $eP_L : mP_n$ represent the de-alignment/re-alignment pathway.

6.1.1 Aims and objectives

The aims of the chapter are as follows:

1) To measure the magnitudes of developments at the three levels of the MLP;

2) To determine the existence and phase of a transition pathway;

3) To identify which pathway is currently underway/likely in the transition;

4) To discuss the possible infrastructural and institutional effects of the emerging pathway(s).

The objectives are:

1) To establish numerical value judgement for landscape, regime and niche developments;

2) To define the relationship between P_L, P_n and R_r in terms of transition;

3) To design values for transition momentum M_t and their trends;

4) To give numerical meaning of pathway determinants, i.e. $P_L : P_n$.

6.1.2 Research approach

The chapter will involve the study of historical transition dynamics to observe how transitions come about in terms of M_t. Important historical transition in the UK electricity generation sector is the ‘dash for gas’ transition; a transition from coal fired electricity regime to natural gas CCGT (combined cycle gas turbine) regime which occurred between the early 1990s and early 2000s (United Kingdom Energy Research Centre [UKERC], 2012). This study will provide numerical meanings to support analysis of future transitions. According to Geels and Schot (2007), empirical levels are initially demarcated to define the scope of socio-technical regimes before operationalizing the multi-level perspective framework. Therefore, the power sector regime may be considered either at a lower level regime of coal fired power generation or a higher level regime of fossil fuel power generation. In the later case, a coal regime transition is viewed as a mere incremental change. Based on transition dynamics that occurred during the dash for gas, present, and most likely future transitions and transition pathways for the fossil fuel regime may be synthesised therefrom.

Because harmful emissions are the most certain and presently occurring landscape element, this work focuses on transitions due to their sole effects as the P_L element. As such, there is every tendency that other unforeseen P_L elements may develop and accelerate the transition process. Another limitation of this work is that actual niche technology development may move at a pace faster than the assumptions made. The analysis will also exclude some renewable energy options for some reasons particular to the UK. Large scale (> 5MW) hydropower sites in the UK have almost been exhausted since 1980 (DECC, 2011) and the main constraint to this option was site (resource) availability. Historical analysis of coal regime transition also excludes renewables such as geothermal, tidal and landfill gas power technologies that suffered tremendous investment constraints during the transition period (DECC, 2011). For fossil fuel regime transition, geothermal and tidal technologies are considered from year 2030 (DECC, 2013).

Concentrations of harmful emissions are considered for the landscape pressure P_L, relative niche technical, economic and sustainability factors are considered for the niche performance P_n, and the fraction of a regime element in the power sector (electricity energy produced/consumed) is considered for the level of regime entrenchment R_r. Numerical and descriptive data from literature are used to develop values for the magnitude of the forces at the landscape, regime and niche levels. Data and information have been obtained from renowned UK government departments and agencies like the Department of Energy and Climate Change (DECC), Committee on Climate Change (CCC), Department for Transport (DfT), and Department for Environment, Food and Rural Affairs (DEFRA).

6.2 Establishing value judgements for developments at the MLP levels

The current electricity regime in the United Kingdom (dominated by fossil fuel technologies) has been embedded within institutions and infrastructure which act as stabilizing forces (DECC, 2014a). On one hand, the regime offers resistance to transition to other (sustainable) alternatives such as nuclear and renewables. On the other, the regime is acted upon by several developments at the landscape level including resource supply issues and atmospheric concentrations of harmful emissions (Foxon et al., 2010). Developments at the niche level also influence the regime by offering alternative technologies with more promising performance relative to the existing regime technology. In this section, we will develop measurement scales for these transitions parameters, namely regime resistance to transition R_r, landscape pressure P_L and technological niche performance P_n.

6.2.1 Measuring regime resistance to transition R_r

The regime is established by a seamless web of heterogonous elements (actors, practices, perceptions, markets, industries) that interact around a particular technology which forms the core of the regime (Kemp et al., 1998). Since the regime is stabilised by three mechanisms of sunk investment, rules and vested interest (Unruh 2000) and since transition is a co-evolutionary process among elements of these mechanisms (Geels, 2002; Geels, 2005a; Geels, 2006a), the entrenchment level of a regime can be a measure of anyone of the three stabilizing mechanisms. Going by the sunk investment mechanism, the maximum regime resistance to change $R_{r.max}$ will occur when the regime technological component is the only source of the products/service without active competitors in an area of social function. The minimum $R_{r.min}$ will be the complete absence of the technology in the production of products/service. For the power sector, we use electricity energy produced/consumed (assuming all electricity energy produced is consumed) by the regime as a fraction (or percentage) of the total to measure its level of entrenchment; with 1 (100%) being $R_{r.max}$ and

0 (0%) being $R_{r.min}$. The future R_r of the fossil fuel regime is projected on the basis of two scenarios; the likely scenario which is based on current transition dynamics and the target scenario based on legally binding targets for alternative energy developments. Table 6.1 below shows historical and future likely and target scenarios of R_r (percent electricity generation by technology) for the various energy sources in the UK's electricity generation portfolio.

Table 6.1. Regime resistance as percentage of electricity generation

Energy source		1980	1985	1990	1995	2000	2005	2010	*2013*	2020	2030	2040	2050
Fossil fuel	Coal $R_{r/c}$	73.2	60.5	65	46.7	32.7	34.5	28.7	35.3				
	Oil $R_{r/o}$	11.7	16.4	10.9	5.20	2.26	1.35	1.27	0.80				
	Gas $R_{r/g}$	0.85	0.98	1.57	19.2	39.6	38.6	46.4	26.7				
	Total $R_{r/ff}'$	85.6	77.9	77.5	71.1	74.5	74.4	76.4	62.7	57.8	45.1	27.2	12.7
	Total $R_{r/ff}''$	85.6	77.9	77.5	71.1	74.5	74.4	76.4	62.7	(50)	(0.0)	(0.0)	(0.0)
	Avg. $R_{r/ff}$	85.6	77.9	77.5	71.1	74.5	74.4	76.4	62.7	53.9	22.6	13.6	6.37
Renewables	Biomass	0.00		0.16		0.45		1.85	3.78				
	Solar PV	0.00		0.00		0.00		0.00	0.57				
	Wind on	0.00		0.00		0.24		1.88	4.83				
	Wind off	0.00		0.00		0.00		0.79	3.24				
	Hydro	1.37		1.64	1.46	1.36	1.24	0.96	1.45				
	Tidal range	0.00		0.00		0.00		0.00	0.00				
	Geothermal	0.00		0.00		0.00		0.00	0.00				
	Landfill gas	0.00		0.03		0.59		1.32	1.48				
	Total $R_{r/r}$	1.57		1.83	2.07	2.66	4.28	6.82	15.5	(30)	(40)	(40)	(40)
Nuclear $R_{r/n}$		13.0		20.7		22.7		16.4	18.2	20	(40)	(40)	(40)
CCS $R_{r/ccs}$		0.00		0.00		0.00		0.00	0.00	0.00	(15)	(15)	(15)
Unabated gas $R_{r/u}$		0.00		0.00		0.00		0.00	0.00	0.00	(5)	(5)	(5)
Total		100		100		100		100	100	100	100	100	100

Sources: CCC (2011b); DECC (2010); DECC (2014); World Bank (2014).

6.2.2 Measuring landscape pressure P_L

Landscape pressures that can affect the UK electricity generation sector and cause transitions include a number of factors such as emissions of harmful gases, concerns on fossil fuel energy supply and its depletable nature, and uncertainty over energy price on the international market (Foxon et al., 2010). However, as mentioned earlier, this work will concentrate on the main cause of historical, present and future transitions in the UK power sector which is atmospheric emissions of harmful gases as the P_L item. This approach will help to ensure if the sole effect of emissions can lead to the desired sustainability. The P_L elements will then be the atmospheric concentrations of GHGs with the consequent effect of climate change and global warming as well as concentrations of sulphur dioxide (SO2), as well as non-CO2 gases such as sulphur dioxide (SO2), nitrous oxides (NOx), particulate matter (PM), volatile organic compounds (VOC) and ozone (O3) with serious effect on human health and the environment (European Environmental Bureau, 2012; Scorecard, 2011). Atmospheric GHG concentrations are more global whereas concentrations of the non-CO2 gases are more local to Europe and thus the relating data are treated as such. Data on concentrations of the non-CO2 gases are collected from prominent cities across the UK including London, Edinburgh, Glasgow, etc. as case study models (Department for Environment, Food, and Rural Affairs [DEFRA], 2013; 2014a, 2014d; Scottish Environment Protection Agency [SEPA], 2008).

To establish measures for the P_L parameters, we consider relevant upper and lower boundaries for each pollutant to represent their concentrations with the extreme and lowest effects respectively. The data variables are then normalised with respective to these boundary limits to define them on a scale of 0 to 1. For atmospheric GHG concentrations, climate change boundary points are used which represent zero and extreme effects of global warming. According to the IPCC (2007a, 2007b), extreme effects of climate change begin at 3 degrees Celsius above the pre-industrial levels. The extreme global mean temperature (GMT) change of 3ºC corresponds to a GHG concentration of 562.5 ppm (IPCC, 2007c) whereas the lowest GMT change of 0ºC corresponds to a GHG concentration of 283.6 ppm, the pre-industrial level (European Environment Agency [EEA], 2012). Atmospheric GHG concentration is more accurate in the measurement of climate change impacts than GMT because there is a time lag between GHG concentrations and GMT rise (Climate Emergency Institute 2014). Thus, historical GMT rise might not make a true real time reflection of the severity of climate change. For the non-CO2 concentrations, starting points for their extreme and lowest effects have been outlined on Table 1 of DEFRA (2013). Table 6.2 below shows historical and estimated future values for the important pollutants, their actual concentrations and the normalised values, as well as their upper and lower boundary limits. The effective landscape pressure $P_{L/eff}$ for a year is the highest landscape pressure for that year. Beyond 2010, only $P_{L/eff}$ due to CO2 is active because non-CO2 gases have been assumed to be mitigated as a result of the 'dash for gas' transition.

Table 6.2. Actual and normalised values for CO2 (annual mean) and non-CO2 (daily mean) concentrations

Pollutant /P_L		**1980**	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**	**2020**	**2050**	**Limits**	
											Uppe	**Low**
CO2eq (ppm)	Act.	373.2	384.5	396.5	405.7	417.5	430.0	443.9	450	550	562.5	283.6
	Nml	0.32	0.36	0.40	0.44	0.48	0.52	0.57	0.60	0.96	1	0
SO2 (μg/m3)	Act.	271.2	85.1	47.5	30	25	25	4			1065	0
	Nml	0.25	0.08	0.04	0.03	0.02	0.02	0.00			1	0
NO2 (μg/m3)	Act.	79.1	74.7	84.7	52	72	62	65			601	0
	Nml	0.13	0.12	0.14	0.09	0.12	0.10	0.11			1	0
O3 (μg/m3)	Act.	122	144	200	173	127	128	123			241	0
	Nml	0.51	0.60	0.83	0.72	0.53	0.53	0.51			1	0
PM_{10} (μg/m3)	Act.			30	28	27	27	18.5			101	0
	Nml			0.30	0.28	0.27	0.27	0.18			1	0
$P_{L/eff}$		0.51	0.60	0.83	0.72	0.53	0.53	0.57	0.60	0.96	0.84	0.41

Source: Den Elzen (2006); Den Elzen and Meinshausen (2005); Den Elzen M. and N. Höhne (2008); DEFRA (2013; 2014a, 2014d); EEA (2012); IPCC (2007); SEPA (2008); Metz (2006).

6.2.3 Measuring niche technology performance P_n

The alternative technologies existing in niches have certain performance potentials which make them feasible options for future deployment at regime levels. Although niche technologies are usually characterised by low technical performance compared to regime technologies (Geels, Hekkert, & Jacobsson, 2008), they hold more sustainability potentials (Witkamp, Raven, & Royakkers, 2011). Their performance may vary and the magnitude of this performance will be a measure of their cost-performance and emissions saving factors with respect to the existing regime. This techno-economic and sustainability performance existing in niches P_n exert an influence on regimes in an attempt to break, penetrate and replace them. Under an imperative for a transition resulting from P_L development, actors consider investment in such niche options and their selection criteria and motivation will depend on P_n in addition to other external factors such as risk perception, availability of resource and actor management style (Chappin et. al. 2007). Usually, each power plant is evaluated against these criteria and the best performing option is considered for investment. Assuming equivalent actor management style and investment risk perception (and hence all criteria hold equal weight among all actors), a niche option that higher P_n factor will then possess higher performance scores and higher chances of forming future regime technology.

The estimated future data on performance-cost (PC) ratios in literature have been further projected to the year 2050 and also back-casted to year 1980 (where applicable) in the order of observed trends. The PC_n for each niche alternative is divided by that of the regime PC_r (coal fired power plant for coal regime transition and fossil fuel power plant for fossil fuel regime transition) to obtain their relative values. Similarly for the sustainability factor, the life cycle emissions intensity EI_n of each alternative power plant has been related to that of the regime EI_r and their relative emission savings ES obtained. The relative emissions savings ES for each power plant is given by the ratio of the difference between EI_r and EI_n to EI_r. This implies that the option with the best emissions performance (a zero EI_n) will have the highest ES factor of 1 and so on. Finally, the niche (technology) performance P_n is computed by multiplying the relative PC values (PC_n/ PC_r) by their relative emissions savings factors ((EI_r – EI_n)/EI_r). Therefore, the niche performance P_n is given by;

$$P_n = \frac{PC_n}{PC_r} \times \frac{EI_r - EI_n}{EI_r} \qquad (6.2)$$

The risk factor of power plants which varies from low (L) through medium (M) to high (H) is considered from a descriptive analysis perspective by taking into account actor attractiveness or aversion to invest in power plant technologies due to their overall risk perception (shown in square brackets on Table 6.3a). Therefore, the risk factor determines the investment decisions of investors in electricity generation plants. However, there are many considerations that affect investment decisions as shown on appendix C. The data on performance-cost (PC) factors and lifecycle emissions intensities (EI) for the various power plants, emissions saving (ES) factors and the resulting niche performance P_n for the various niche technology options as computed from equation (6.2) are presented in Tables 6.3a&b below. Note that for fossil fuel regime, EI_{ff} varies continually over the period 1980-2050 because of the continually changing proportions of coal, oil and gas forming the fossil fuel regime generation portfolio. However, the year 2013 proportion has been assumed for the years beyond to 2050.

Table 6.3a. Data on P_n parameters of important alternative power plant technologies under coal regime transition in the UK

	Pollutant	**CO2eq ($x10^3$)**	**SO2**	**NOx**	**VOC**	**PM**	**Total ($x10^3$)**	**Coal relative ES factors**	
Lifecycle EI of power plants (t/TWh) [risk perception shown in brackets]	Coal [H]	1082	1490	2928	29	190	1087	0.00	
	Oil	778	1550	12300	0	122	792	0.27	
	Gas ccgt [L]	453	0	494	132	1	454	0.58	
	Coal igcc w ccs [H]	174	200	700	0	30	175	-	
	Gas ccgt w ccs [H]	35.8	0	494	132	1	36.4	-	
	Nuclear conv. [H]	4	50	15	0	2	4.01	1.00	
	Nuclear new [H]	4	50	15	0	2	4.01	1.00	
	Biomass [M]	0	0	0	0	0	0	1.00	
	Solar PV [L]	0	0	0	0	0	0	1.00	
	Wind onshore [L]	0	0	0	0	0	0	1.00	
	Wind offshore [M]	0	0	0	0	0	0	1.00	
	Tidal [H]	0	0	0	0	0	0	1.00	
	Geothermal [H]	0	0	0	0	0	0	1.00	
	Year	**1980**	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**	**2013**
PC factors (MWh/£1000)	Coal	10.53	10.53	10.53	10.53	10.53	10.53	10.53	10.53
	Gas CCGT	16.67	15.70	14.71	14.29	13.51	13.16	12.50	12.35
	Nuclear conv.	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11
	Biomass	8.24	8.29	8.34	8.39	8.43	8.50	8.54	8.52
	Solar PV	2.78	3.10	3.43	3.84	4.30	4.90	5.72	6.18
	Wind onshore	7.80	8.00	8.10	8.27	8.41	8.56	8.76	8.89
	Wind offshore	3.33	3.80	4.04	4.49	5.06	5.63	6.35	6.67
Niche performance P_n	Coal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Gas – ccgt	0.92	0.87	0.81	0.79	0.75	0.73	0.69	0.68
	Nuclear	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
	Biomass	0.78	0.78	0.79	0.80	0.80	0.81	0.81	0.81
	Solar PV	0.26	0.30	0.33	0.36	0.41	0.47	0.54	0.59
	Wind onshore	0.74	0.75	0.77	0.79	0.80	0.81	0.83	0.84
	Wind offshore	0.32	0.35	0.38	0.43	0.48	0.54	0.60	0.63
	$P_{n/eff}$ ($P_{n/ccgt}$)	0.92	0.87	0.81	0.79	0.75	0.73	0.69	0.68

Source: Alberici et al. (2014); Berry et al. (1998); CCC (2011a); DECC (2012a, 2012b); DECC (2013a, 2013b); Harris et al. (2012); IEA (2000); IEA (2003); Odeh, Hill and Forster (2013).

Table 6.3b. Data on P_n of important alternative power plant technologies under fossil fuel regime transition in the UK

	Year		**1980**	**1990**	**2000**	**2010**	***2013***	**2020**	**2030**	**2040**	**2050**
Energy generated, emissions & EI of fossil fuel regime	Coal	TWh	207.9	206.4	122.3	108.8	124.1				
		mtco2eq	225.9	224.3	132.9	118.2	134.9				
	Oil	TWh	33.14	34.68	8.45	4.81	2.81				
		mtco2eq	26.25	27.47	6.69	3.81	2.23				
	Gas ccgt	TWh	2.12	5	148.1	175.7	93.8				
		mtco2eq	0.96	2.27	67.17	79.68	42.55				
	Fossil fuel	TWh	243.2	246.1	278.8	289.3	220.7				
		mtco2eq	253	254	206.8	201.7	204.1				
	EI_{ff}	mt/TWh	1.04	1.03	0.74	0.70	0.81	0.81	0.81	0.81	0.81
Relative ES factors	Coal igcc w ccs		-	-	-	-	-	0.71	0.71	0.71	0.71
	Gas ccgt w ccs		-	-	-	-	-	0.96	0.96	0.96	0.96
	Nuclear		1.00	1.00	0.99	0.99	1.00	1.00	1.00	1.00	1.00
	Renewables		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
PC factors (MWh/£1000)	Fossil fuel conv.		9.05	9.03	11.45	11.39	10.99	10.99	10.99	10.99	10.99
	Coal IGCC w ccs		-	-	-	-	-	7.41	7.52	7.69	7.87
	Gas CCGT w ccs		-	-	-	-	-	10.53	10.53	10.53	10.53
	Nuclear conv.		11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11	11.11
	Nuclear EPWR		-	-	-	-	-	11.76	13.70	16.39	22.22
	Biomass		8.24	8.34	8.43	8.54	8.52	8.66	8.73	9.07	9.13
	Solar PV		2.78	3.43	4.30	5.72	6.18	8.07	10.56	13.39	17.42
	Wind onshore		7.80	8.10	8.41	8.76	8.89	9.17	9.32	9.54	9.72
	Wind offshore		3.33	4.04	5.06	6.35	6.67	7.89	8.70	10.47	13.33
	Tidal range		-	-	-	-	-	-	4.35	4.35	4.35
	Geothermal		-	-	-	-	-	-	10	10	10
Niche performance P_n	Coal igcc with ccs		-	-	-	-	-	0.47	0.49	0.50	0.51
	Gas ccgt with ccs		-	-	-	-	-	0.92	0.92	0.92	0.92
	CCS avg. $P_{n/ccs}$		-	-	-	-	-	0.69	0.70	0.71	0.71
	Nuclear (conv)		1.22	1.23	0.97	0.97	1.01	-	-	-	-
	Nuclear EPWR		-	-	-	-	-	1.07	1.24	1.48	2.01
	Biomass		-	0.92	0.74	0.75	0.78	0.79	0.79	0.83	0.83
	Solar PV		-	0.38	0.38	0.50	0.56	0.73	0.96	1.22	1.59
	Wind onshore		-	0.90	0.73	0.77	0.81	0.83	0.85	0.87	0.88
	Wind offshore		-	0.45	0.44	0.56	0.61	0.72	0.79	0.95	1.21
	Tidal range		-	-	-	-	-	-	0.40	0.40	0.40
	Geothermal		-	-	-	-	-	-	1.01	1.06	1.11
	Ren. avg. $P_{n/ren}$		-	0.66	0.57	0.64	0.69	0.77	1.20	1.33	1.51
	$P_{n/eff}$ ($P_{n/ren}$)		-	0.66	0.57	0.64	0.69	0.77	1.20	1.33	1.51

Source: Alberici et al. (2014); Berry et al. (1998); CCC (2011a); DECC (2012a, 2012b, 2013a, 2013b); Harris et al. (2012); IEA (2000, 2003); Odeh, Hill and Forster (2013); World Bank (2014).

6.3 Analysis and Discussion

6.3.1 Historical transition of coal power regime

As mentioned earlier, our historical case study of socio-technical transition in the UK was the 'dash for gas' transition of coal fired power generation to natural gas CCGT. Until the early 1990s, the regime in the UK electricity generation sector has been coal fired power system along with other important sources such as hydro, nuclear and oil (DECC, 2014a; World Bank, 2014). Since 1980, there has been continuous emission of GHGs and other harmful non-CO2 gases such as sulphur dioxide (SO2), nitrogen oxides (NOx), non-methane volatile organic compound (NMVOC) and dust or particulate matter (PM) as well as a secondary pollutant of ground level ozone (O3) (DEFRA, 2014; Leonardo Academy, 2013). In Europe during the 1980s, landscape impact due to concentrations of the non-CO2 gases needed immediate attention because of concerns on their negative consequence. These include acidifications to soil and freshwater bodies, damages to plants and aquatic habitats, corrosion to building materials and ozone formation with damaging effects to human health (Air Pollution Information System, 2014; Parliamentary Office of Science and Technology, 2002).

In the UK, power generation sector remained the major source of such emissions (DEFRA, 2010, 2014b, 2014c; National atmospheric emissions inventory [NAEI], 2015). During the 1980s, the landscape impact of the non-CO2 emissions put an increasing pressure (changing from medium to high) on the emitting sectors (mainly electricity generation) as shown on Figure 6.1. This landscape development engendered the need for a transition from emissions intensive coal regime to an alternative regime with low emissions. The effective pressure $P_{L/eff}$ was peaking to a very high value towards year 1990 during which time the first large combustion plants directive (88/609/EEC) was implemented in 1988 to set emission ceilings for SO2 and NOx to be achieved between 1993 and 2003 (Eames, 2000; European Commission, 2006). Also, continuous emissions of GHG throughout the industrial era have been forecasted to cause significant climate change with consequent effect of global warming (IPCC, 2007b). This development also led to the first IPCC's assessment report in 1990 which considered a scientific evaluation of existing and likely future effects of climate change. The landscape pressure forced regime actors to consider investment in other sustainable alternatives.

The technological niche level comprised several potential electricity generation technology alternatives including the natural gas CCGT, solar, wind, biomass, with varying degrees of maturity (Shackley & Green, 2006). The penetration potentials of the niche alternatives will depend on their techno-economic and sustainability performance P_n, and other external factors of resource availability and the level of overall risk perception (indicated in square brackets as shown on Figure 6.1). During this time, renewable options had very low P_n (Mitchell, 1996) whereas potential for gas CCGT was offset by high natural gas prices (UKERC, 2012). On the other hand, nuclear power potential was downplayed by the UK's anti-nuclear movement in the 1980s which received a further boost from the 1986 Chernobyl nuclear plant disaster in Ukraine (Rothwell, 2014).

This difficult time for a transition came to an end at around the late 1980s when in addition to its low risk level, the economic viability of CCGT technology improved due to higher technical efficiency (UKERC, 2012) and availability of cheap gas from the North Sea (DECC, 2014a; Shackley & Green, 2006). Around the same time, the landscape pressure was at its peak (P_L > 0.8). The correspondence of this very high pressure P_L with the high CCGT's niche performance $P_{n/ccgt}$ in the order of 0.8, the transition gained higher momentum M_t, indicating successful processes of transitions. The transition started from the late 1980s and accelerated to its stabilisation phase in the early 2000s in not much more than a decade (Shackley & Green, 2007). During this period, natural gas CCGT grew from almost 0%

around the 1990 to a dominant position of 40% in 2000, replacing coal fired power regime (World Bank, 2014). As a result, the main emissions that constituted the landscape pressure (i.e. SO2, NO2, NMVOC, O3 & PM) have been reversed (Figure 6.1).

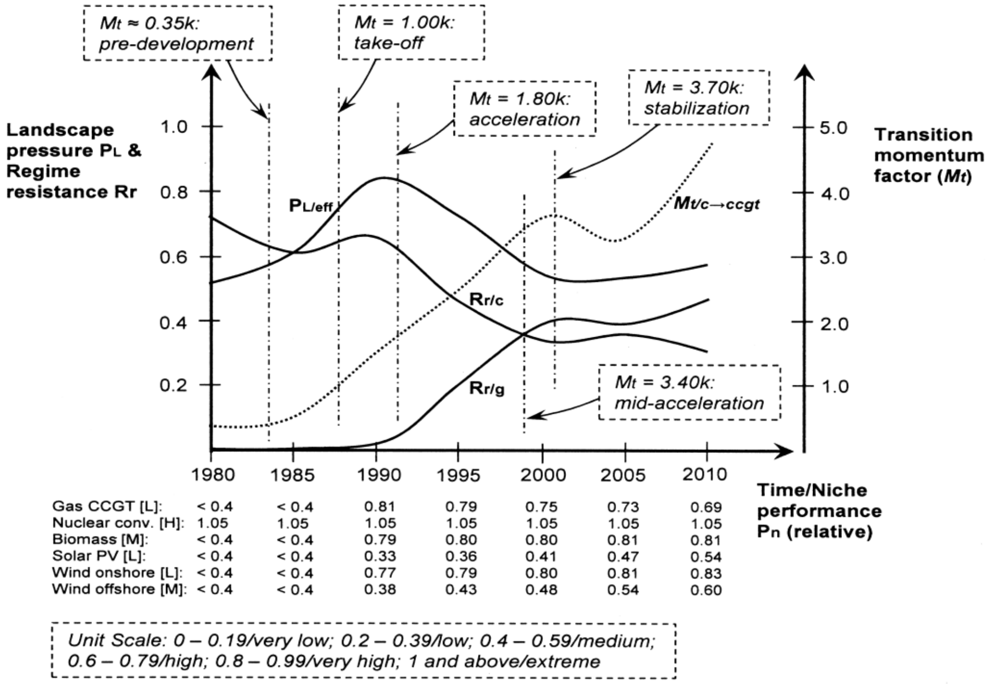


Figure 6.1. Analysing the 'Dash for gas' transition in the UK electricity generation

(Data source: Alberici et al., 2014; Berry et al., 1998; CCC, 2011a, 2011b; DECC, 2010, 2012a, 2012b; 2013a, 2013b, 2014; DEFRA, 2013; 2014a, 2014d; Den Elzen, 2006; Den Elzen & Höhne, 2008; Den Elzen & Meinshausen, 2005; EEA, 2012; Harris et al., 2012; IEA, 2000, 2003; IPCC, 2007; UKERC, 2012; Metz, 2006; Odeh et al., 2013; SEPA, 2007; World Bank, 2014)

The trend for the transition momentum for coal-CCGT transition $M_{t/c\rightarrow ccgt}$ can be computed from equation (6.1) of section 6.1 using corresponding values of $R_{r/c}$, $P_{L/eff}$, and $P_{n/eff}$ from Tables 6.1, 6.2 and 6.3a according to the following expression:

$$M_{t/c\rightarrow ccgt} = k\,\frac{P_{L/eff}\,P_{n/eff}}{R_{r/c}^{2}} \qquad (6.3)$$

Values for $M_{t/c\rightarrow ccgt}$ before 1990 can be approximated by assuming intermediate values for the low P_n which ranged between 0.2 and 0.39, i.e. P_n = 0.3. At the beginning of transitions, actors respond to P_L by modifying their trajectories of development for sustaining the existing regime. The momentum M_t will begin to increase as P_n increase and/or R_r decrease due to alternative investments. If actors succeed in mitigating P_L before M_t reaches 1.0k (regime cracking point), then the momentum of the transition reverses and the transition ends through a transformation pathway. However, when M_t reaches 1.0k for a transition, the pathway will be one of the regime change pathways, i.e. reconfiguration, substitution or de-alignment/re-alignment depending on the ratio P_L : P_n. The phases of transition will be determined by certain values of M_t along its trend. Since regimes begin to crack at $M_t = 1.0k$, it may be said that for regime change pathways, the pre-development phase of the transition will begin at a value of $M_t < 1.0k$.

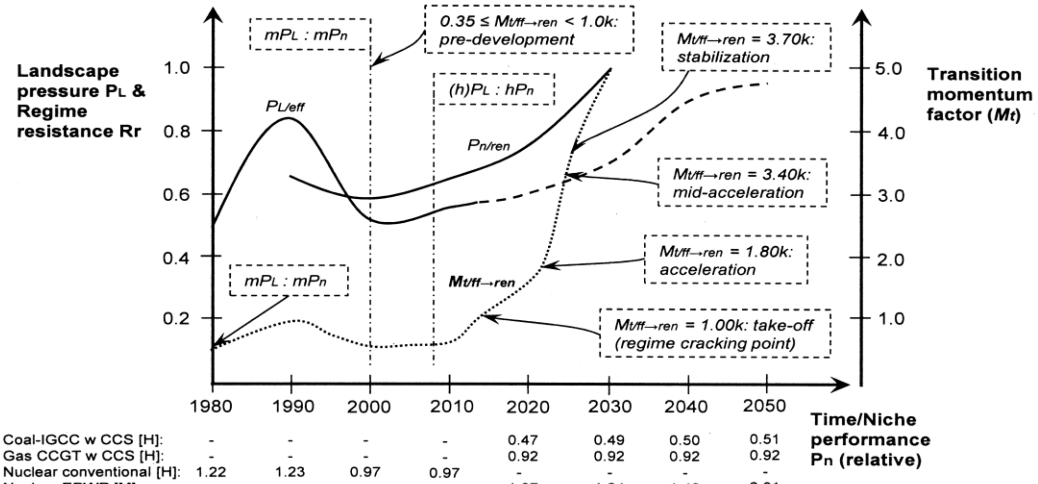
Therefore, a close observation of $M_{t/c \rightarrow ccgt}$ and R_r trends of coal-CCGT transition (Figure 6.1) may justify the following results; the pre-development phase of the transition began around 1983 and corresponds with an $M_t \approx 0.35k$, the take-off phase started around 1987 and corresponds with the regime cracking point of $M_t = 1.0k$, the acceleration phase started at 1992 and corresponds with an $M_t = 1.80k$, whereas the stabilisation phase began at 2001 and corresponds with an $M_t = 3.7k$. The meeting point of the old and new regime technologies is an important point during the transition marking the mid-acceleration phase and corresponds with an $M_t = 3.4k$. The transition started at a point of a very high P_L (0.85) and a high P_n (0.69), i.e. the pathway is characterised by vP_L : hP_n resulting to a substitution transition with a rapid process. These M_t values are generic and may be extended to any socio-technical regime transition process for purposes of analysis.

6.3.2 Current transition of fossil fuel power regime

In a similar approach, the M_t trend for the transition of fossil fuel to an alternative x, i.e. $M_{t/ff \rightarrow x}$ can be computed from equation (6.1) using relevant data on $R_{r/ff}$, $P_{L/eff}$, and $P_{n/eff}$ from Tables 6.1, 6.2 & 6.3b as follows:

$$M_{t/ff \to x} = k \frac{P_{L/eff} P_{n/eff}}{R^2_{r/ff}} \qquad (6.4)$$

Hence, identifying the previous M_t values along the $M_{t/ff \to x}$ trend will indicate whether or not a transition of fossil fuel power regime in the UK has started, and in a transition case, the stage (phase), progress and likely end of the transition. Alternatives to fossil fuel regimes are nuclear (new generation), renewables and CCS (carbon capture and storage) technologies. Of these, the currently socially and economically feasible option is the renewable power technologies (DECC, 2013). This implies that the transition momentum will be $M_{t/ff \to ren}$ and the calculation thereof will consider the effective niche performance $P_{n/eff}$ for the renewable energy option $P_{n/ren}$ as shown in Table 6.3b. Figure 6.2 below shows trends of the effective landscape pressure $P_{n/eff}$, effective niche performance $P_{n/ren}$ and the relevant transition momentum $M_{t/ff \to ren}$.



	1980	1990	2000	2010	2020	2030	2040	2050
Coal-IGCC w CCS [H]:	-	-	-	-	0.47	0.49	0.50	0.51
Gas CCGT w CCS [H]:	-	-	-	-	0.92	0.92	0.92	0.92
Nuclear conventional [H]:	1.22	1.23	0.97	0.97	-	-	-	-
Nuclear EPWR [M]:	-	-	-	-	1.07	1.24	1.48	2.01
Biomass (ded./conv.) [M]:	< 0.4	0.92	0.74	0.75	0.79	0.79	0.83	0.83
Solar PV [L]:	< 0.4	0.38	0.38	0.50	0.73	0.96	1.22	1.59
Wind onshore [L]:	< 0.4	0.90	0.73	0.77	0.83	0.85	0.87	0.88
Wind offshore [M]:	< 0.4	0.45	0.44	0.56	0.72	0.79	0.95	1.21
Tidal [H]:	< 0.4	-	-	-	-	0.40	0.40	0.40
Geothermal [H]:	< 0.4	-	-	-	-	1.01	1.06	1.11
Ren. avg. $P_{n/ren}$ [M]:	< 0.4	0.66	0.57	0.64	0.77	1.20	1.33	1.51

Unit Scale: 0 – 0.19/very low; 0.2 – 0.39/low; 0.4 – 0.59/medium; 0.6 – 0.79/high; 0.8 – 0.99/very high; 1 and above/extreme

Figure 6.2. Analysing transition of fossil fuel regime in the UK electricity sector

(Data source: Alberici et al., 2014; Berry et al., 1998; CCC, 2011a, 2011b; DECC, 2010, 2012a, 2012b, 2013a, 2013b, 2014; DEFRA, 2013, 2014a, 2014d; Den Elzen, 2006; Den Elzen & Höhne, 2008; Den Elzen & Meinshausen, 2005; EEA, 2012; Harris et al., 2012; IPCC, 2007; IEA, 2000, 2003; UKERC, 2012; Metz, 2006; Odeh et al., 2013; SEPA, 2007; World Bank, 2014)

6.3.3 Observation

Using the three levels of the MLP framework as determinants of socio-technical transitions, important message can be synthesised from the analytic results of the UK's prominent 'dash for gas' transition. Figure 6.2 above shows the $M_{t/ff\rightarrow ren}$ trend for fossil fuel electricity regime transition. Since 1980 and up to around 2000, the transition momentum indicated that the UK fossil fuel electricity regime transition has been characterised by a non-regime change scenario; the transformation pathway ($M_{t/ff\rightarrow ren} < 1.0k$). Between 1980-1990, the transition has been characterised by an increasing momentum, declining thereafter to a lower level due to the transformation process (the coal-CCGT transition appears as a transformation from a fossil fuel regime perspective). This process mitigated the main landscape pressure due to non-CO2 emissions that caused the transition. The regime has gained a modest stability during the period 2000-2010 as a result of this 'internal restructuration'. However, M_t for this stability period has been greater than the starting point of a predevelopment phase, i.e. $M_{t/ff\rightarrow ren} > 0.35k$. This implies that the regime after the transformation transition has not stabilised fully but maintained a predevelopment phase to another transition.

For the transition of fossil fuel regime, the currently existing and apparently growing item of the landscape development is the atmospheric GHG concentrations resulting from continuous carbon emissions. The effects of these gases have been estimated by the IPCC (2007) to be around moderate in the first decade of the 21st century, but their rates of growth are very alarming. According to a central case scenario (Figure 6.2), $P_{L/co2eq}$ will attain high effects of 0.6 (i.e. 450ppm) by 2020 and very high effects of 0.96 (i.e. 550ppm) towards the year 2050 at the global level. Since the power sector in the UK is only a tip of the iceberg when viewed on a global scale, it may be assumed that any form of changes in emissions from this sector may not make significant deviation from such projected scenarios for $P_{L/co2eq}$ (this explains why $M_{t/ff\rightarrow ren}$ trends look steeper even at stabilisation region as shown on Figure 6.2).

Therefore as carbon emissions continued to intensify their effect at the landscape level beyond 2000, the transformation transition appeared to be insufficient to put the fossil fuel power regime on the path of sustainable development. The regime was faced with another landscape challenge that necessitated the need for a renewed approach in tackling emissions from conventional fossil fuel power plants; a need for a further transition of the wider regime. As a result, $M_{t/ff \rightarrow ren}$ encountered a turning point around 2010 and took another dimension of growth for the new transition process.

6.4 Conclusion

In this chapter, we established measurement techniques for the three basic transition determinants, i.e. regime resistance R_r, landscape pressure P_L, and technological niche performance P_n to study transitions and transition pathways. A secondary quantity that determines the status of a transition, the transition momentum M_t is derived from the three quantities based on the principle of proportionality. From the UK's 'dash for gas' transition, certain M_t values have been identified at important points along its trend to represent key features of a transition process. These M_t values are used to analyse the wider regime of fossil fuel power generation. The result shows that the period 1980-2000 has been characterised by a period of transformation transition. The pre-development phase (also a transformation process) to a substitution pathway to renewable electricity occurs around the period 2000-2013, the take-off phase around the mid-2010s, the acceleration around the early 2020 and the stabilisation around the mid-2020. The emergence of a single power technology regime to replace the current natural gas combined cycle gas turbine (CCGT) regime will most likely follow the de-alignment/re-alignment pathway. In this pathway, the regime will be characterised by loosely coupled distributed generation where bidirectional flows are necessary to balance demand and supply. Smart grids are crucial for a smooth operation of the system.

CHAPTER 7

OVERALL CARBON PERFORMANCE IN THE UK

7.1 Introduction

Using historical data, this chapter provides an assessment of the changes that have taken place in the UK's energy systems due to decarbonisation in response to transition policies over the past two decades. The chapter examines the efforts directed towards low-carbon energy production and consumption such as the setting of sustainability standards, resource-efficient system and the shifts from high to low carbon-intensive fuels. The assessment is done by identifying the key indicators of change such as energy intensity and consumption, GHG intensity and emissions, technology, policy and regulatory measures, considering current transition dynamics. This helps in shedding light on the future prospects of the range of potential technologies as well as changes on the demand side.

7.2 Carbon reduction progress assessment

As a developed country which is a party to the Kyoto Protocol under Annex I (Appendix A), the UK has a legally binding commitment of reducing its GHG emissions to at least 92% against its 1990 emission figures during the first commitment period of 2008-2012 (UNFCCC, n.d.). The EU–15 has committed to reduce its collective ghg emissions to 8% below the 1990 level in the period 2008-2012 (European Commission, 2015). The 8% collective reduction commitment has been split among the EU – 15 member countries under the "burden sharing" agreement. Between the period 2008-2010, the EU-15 as a whole is almost 2% below the target, over-achieving its Kyoto target (Haita, 2012). Within the EU-15, the United Kingdom can be said to be among the EU-15 countries that have absorbed the excess in other members by over-achieving its burden sharing commitment by a wide margin.

Emissions in the UK have fallen from 783.41mtco2eq to 586.36mtco2eq between 1990 and 2012 (UNFCCC, 2014c). Table 7.1 below shows a summary of the report on UK's low carbon transition status.

Table 7.1. Emissions reduction targets and progress in the UK

Base year/Reference figure		1990	783.41 mtco2eq at base year
Kyoto Protocol (burden sharing) reduction commitments		1st period (2008-2012)	12.5% below base yr level
		2nd period (2013-2020)	20% below (EU)
IPCC reduction recommendations		2020	25-40% below by 2020
		2050	80-95% below by 2050
Carbon Budgets	**Overall target**		at least 80% below by 2050
	1st carbon budget (2008-2012)	3,018 mtco2eq – budget level	23% below
	2nd carbon budget (2013-2017)	2,782 mtco2eq – budget level	29% below
	3rd carbon budget (2018-2022)	2,544 mtco2eq – budget level	35% below by 2020
	4rd carbon budget (2023-2027)	1,950 mtco2eq – budget level	50% below by 2025
Progress assessment (as at 2012)		Carbon budget progress: 3017.24 mtco2eq by 2012	Target over-achieved by 0.025%
		Kyoto Protocol progress: 25.15% below 1990 level by 2012	Target over-achieved by 101.2%
		Remark	UK is on track

Source: CCC (n.d.b); European Commission (2015); UNFCCC (2014a, 2014c).

7.3 Impact of energy transition pathways on carbon performance in the UK

Different transition pathways have different impact on the overall GHG mitigation in the UK. Under this section, observation is made on the impact of the relevant transition pathways.

7.3.1 Impact of reproduction and transformation pathways

Energy-efficiency has proved to be an important tool in transforming markets and stimulating adoption of new, more efficient technologies and products. The adoption of more energy efficient appliances and lighting is made possible through setting standards and labelling items (standards and labels) for easy identification. Standards and labels programmes are among the most cost-effective instruments in reducing GHG emissions. Products subject to standards or labels cover all end-uses and fuel types, with a focus on appliances, information and communications devices, lighting, heating and cooling equipment and other energy-consuming products. Despite widely divergent approaches, national S&L programmes have resulted in significant cost-effective GHG savings (IPCC, 2007d).

7.3.1.1 Energy consumption and GHG emissions

Energy intensity in the UK has been decreasing since 1990, from around 150.35 to 87.15 koe/$1000GDP (constant 2011 international $) between 1990 and 2012 (World Bank, 2014). Reproduction and transformation have played important roles in controlling energy consumption through energy efficiency measures. Without these instruments, energy consumption and the resulting emissions would have been more than the current figures. The contribution of reproduction and transformation pathways in reducing energy consumption and GHG emissions in the UK (Appendix D) is as shown on Figure 7.1 below. As climate change awareness and mitigation strategies increase, it is likely that the UK will increasingly prioritise energy efficiency as a critical solution to reducing greenhouse gas emissions.

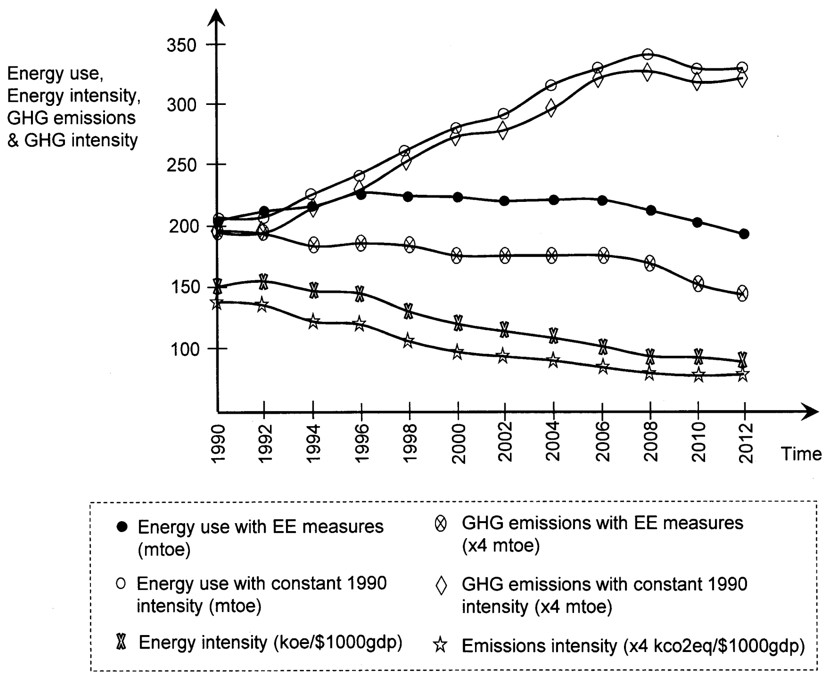


Figure 7.1. Observing the impact of energy efficiency measures on energy consumption and GHG emissions in the UK (UNFCCC, 2014c; World Bank, 2014)

Industry is the main sector driving energy intensity reduction in industrialised countries. In the case of UK, energy productivity improvements were largely driven by industry. The energy efficiency of energy intensive industries, e.g. steel, and cement, is converging and improving rapidly as a result of ongoing globalisation. Service sector energy intensity in the UK is also decreasing because energy efficiency has played an important role in energy consumption reduction. In the transport sector, energy consumption is growing much slower than the GDP. Similarly, there is a positive contribution of energy efficiency to energy consumption in the agricultural sector. Higher energy standards for houses and the introduction of more efficient electrical appliances and heating installations have not led to a decrease in total energy and electricity consumption by households (DECC, 2014b; Enerdata, 2015; World Bank, 2014).

Energy efficiency is widely viewed as an inexpensive way to reduce energy consumption and drive reductions in global emissions of greenhouse gases. In recent years, energy policies are more towards raising energy-efficiency standards on consumer devices, such as refrigerators and washing machines. Market transformation has been a preferred policy approach to promoting energy efficiency, whereby standard setting and labelling of consumer products has been used to accelerate the adoption of more efficient products. A combination of national incentives such as energy labelling, minimum performance standards and energy efficiency policies have proven to be successful for the so-called white appliances like freezers, washing machines and dishwashers. For example, the UK's total residential energy consumption has dropped between 2004 and 2014 by 11.171 ktoe (DECC, 2014b), mainly due to better insulated buildings and boilers, resulting from the EU's requirements on energy performance of buildings and national measures to promote them.

7.3.1.2 Limitations of energy efficiency on transition

While energy efficiency plays an important role in energy and emissions savings on one hand, on the other hand socio-cultural changes in the landscape is adding more pressure on energy demand. Cultural shifts have been towards more individualisation; implying fewer persons per household, more private ownership and use of vehicles, more extended mobility patterns and higher expectations concerning fulfilment of individual lifestyle aspirations (with electrical devices replacing non-electrical ones, e.g. electric toothbrushes or carving knives). Increase in affluence result to continuous introduction of new products and increased equipment ownership, thereby increasing the quantity of energy services required per capita. The result is a corresponding growth in energy consumption (Shackley & Green, 2007).

Hence, despite an increase in energy efficiency that results to decrease in energy intensity of -41% between 1990 and 2013, the total energy consumption in the UK (which falls by -3.64%) has not decreased in the same measure (Enerdata, 2015; DECC, 2014b). Domestic ownership and use of cars and electronic equipment, including cell phones, iPods, PCs, etc. have increased demand for energy use from 474 TWh (40756 ktoe) in 1990 to 502 TWh (43720 ktoe) in 2012 (DECC, 2013c, 2014b), and hence more carbon emissions from coal and natural gas plants. Therefore, electricity use in households is growing rapidly despite more efficient appliances. The effects of the socio-cultural landscape trends upon consumption are putting pressure on the effect of efficiency improvements and are undoing efforts toward reduction of energy demand.

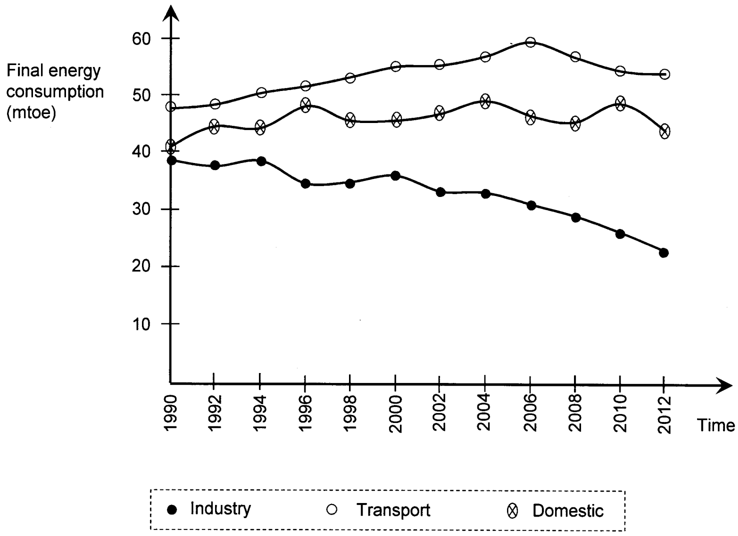


Figure 7.2. Historical energy consumption in the UK (DECC, 2013c, 2014b)

7.3.2 The impact of substitution pathway

The substitution pathway comes about as a result of the substantial change in the energy mix of a country. Between 1990 and 2012, the UK achieved different levels of change in its energy mix in an effort to reduce its CO2 emissions. Within this period, the UK achieved a transition through substitution by moving from coal as a major source of electricity to CCGT (DECC, 2014b; World Bank, 2014). However, fuel choice to a large extent is sector dependent (coal for dominant processes in the iron and steel industry, oil products in large sectors in the chemical industry). Nevertheless, there is some progress towards an overall low carbon economy as illustrated in Table 7.2 below.

Table 7.2. The impact of substitution in the UK (1990-2012)

Consumption Sector	**Technology/ Conversion Fuel**	**Actual quantity of energy**		**% of total sector energy**	
		1990	**2012**	**1990**	**2012**
Electricity/Heat production (Power plants)	Coal (TWh)	206.438	143.619	64.968	39.87
	Oil (TWh)	34.676	3.550	10.913	0.986
	Gas (TWh)	4.998	99.745	1.573	27.690
	Nuclear (TWh)	65.749	70.405	20.692	19.545
	Renewables (TWh)	5.811	41.141	1.829	11.421
Transport (Vehicles)	Biomass (ktoe)	0	958	0	0.017817
	Electricity (ktoe)	0	2	0	0.000037196

Sources: DECC (2014b); World Bank (2014).

7.4 Conclusion

In the reproduction and transformation pathways, energy efficiency has played an important role because if technologies and economic structures in the UK had remained at their 1990 level, it would have consumed more energy in 2013. Whilst steady incremental innovation towards efficiency is capable of making a major contribution to energy intensity (energy consumption per unit of economic activity) over time, this does not equate to a reduction in overall energy consumption. There is evidence that savings made by energy efficiency in one domain result in increased consumption elsewhere in the economy. Only by far more significant government intervention would it be possible to re-direct energy efficiency savings towards zero- or low-carbon energy intensive activities. Such levels of intervention are currently beyond the perceived role of government in society, as ruled out by the landscape level. The subsequent substitution pathway is towards low carbon electricity and transport. Investment in renewables technologies such as CHP and renewables such as wind, solar, hydro and biomass are still actually negligible.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Transition pathway sequence

An additional depth of literature based analysis of transition pathways has been established to further enhance understanding of their characteristic distinctions and sequential linkages. Going by the direction of increase in landscape pressure P_L, transitions start with the transformation pathway (T), through the reconfiguration (R) and substitution (S), and finally de-alignment/re-alignment pathway (D/R), i.e. T-R-S-D/R. Going by maturity level of niche technologies (NTs) γ_n, the sequence will be T, through R or D/R and finally S, i.e. T-R-D/R-S. The P_L axis separates R & D/R at about the same γ_n levels whereas the $\gamma_n(t)$ axis separates R & S at about the same P_L levels. It has been noted that whether D/R or S succeeds R depends on the differences of $P_{Lt.D/R} - P_{Lt.R}$ and $\gamma_{n.S} - \gamma_{n.R}$ and the rates of change of P_L and γ_n. An increase in $P_L/\gamma_n(t)$ or a smaller $P_{Lt.D/R} - P_{Lt.R}$ than $\gamma_{n.S} - \gamma_{n.R}$ favours the sequence T-R-D/R-S whereas a decrease in $P_L/\gamma_n(t)$ or a larger $P_{Lt.D/R} - P_{Lt.R}$ than $\gamma_{n.S} - \gamma_{n.R}$ favours the sequence T-R-S-D/R. In the case of equivalent change rates of P_L and $\gamma_n(t)$ from R, and where the $P_{Lt.D/R} - P_{Lt.R}$ and $\gamma_{n.S} - \gamma_{n.R}$ differences are not too wide, a fifth scenario (X) which combines part characteristics of both D/R and S has been observed. Where this assumption does not hold, X is unstable and the measure of D/R and S features therein depends on its location in triangle b-D/R-S.

Another determinant of X feature with respect to D/R and S is the instantaneous rate of change $\delta P_L/\delta\gamma_n(t)$. X is D/R biased when the slope $\delta P_L/\delta\gamma_n(t)$ increases and is S biased when $\delta P_L/\delta\gamma_n(t)$ decreases. An additional factor determining X feature is the number of emerging alternative technologies associated with it. Also, an indirect factor that affects the sequence of transition pathways is the pathway history of a transition. A transition that has involved more of the first two pathways (T and R) is likely to acknowledge S as the next scenario to R because in this transition, P_L is not fully cumulative due to the actions of T and R which reduce the growth rate P_L/t of landscape pressure. Subsequently, a slow P_L may affect a timely attainment of $P_{Lt.D/R}$ required to trigger D/R, therefore T-R-S-D/R is likely. Another indirect factor is the influence of government policies which promotes the development and adoption of niche technologies during a transition.

8.2 The transition prospect of UK road transport

The low carbon transition in the UK road transport sector has been explored and analysed using the theory of socio-technical transition pathways. The dynamics are those of transformation pathway with some characteristics of a reconfiguration scenario resulting from technology alignment in electric vehicles. However, the technology alignment that has occurred in the EV industry (characteristic of reconfiguration) and their emergence in the road sector (characteristic of substitution) did not have a radical impact on the regime, but has been confined to specific niches, an apparent characteristic of transformation pathway. As climate change and energy supply issues are global and need attention, there will be persistent pressure at least on UK energy systems toward full decarbonisation. However, the transformation pathway which included biofuel blends ICEs and niche ULEVs leaves the regime with a considerable carbon emission characteristic. Therefore, transformation in such context is obviously insufficient to achieve the UK low carbon transition ambition for the road sector. This implies that other transition pathways are needed for a full-scale decarbonisation.

The necessity for other more radical pathways is further inevitably corroborated by the fact that as the landscape pressure has steadily risen to that of transformation in recent times, it will almost certainly not take long to attain those of reconfiguration and substitution.

Moreover, if proper precautions are not taken, de-alignment/re-alignment pressures might prevail. However, as the landscape pressure intensifies, renewed approaches are expected by the UK toward enhancing decarbonisation through large-scale investment in and support for the uptake of ULEVs. With adequate technology breakthroughs, the technical capability of the UK vehicle industry might be adequate to accommodate any severe landscape development and the accompanying strict policy measures. This case implies that a successful transition can occur through any of the high niche-demanding pathways beyond the transformation to bring about much needed radical change. However, in the face of accelerating threats from landscape developments, especially that of climate change, the UK cannot afford to rely on such uncertain super innovations.

The current maturity levels of niche innovations in the UK road vehicles sector are those of low hydrogen FCV and semi-matured BEV corresponding with moderate to high landscape pressures. This pressure is obviously growing, although it has not yet reached the stage of de-aligning the dominant fossil fuel road vehicle regime. Such a combination of niche innovation and landscape pressure levels suggest that transformation pathways should have already been taking place, while dynamics of reconfiguration and substitution pathways should be evident. The possibility for reconfiguration transition is linked to the distributed technology nature of BEV in areas of charging points and battery technologies, whereas feasibility for substitution lies in the technology's considerable level of maturity in various niches. Findings show that although the transformation is the most established and broad pathway somewhere at the take-off phase, reconfiguration and substitution scenarios in BEV are building up momentum and their emergence are not unlikely in the near future. The hydrogen FCV also holds similar pathway potentials but are likely to be delayed in view of its current low level of development. However, the transition may seem to come about through a likely pathways' sequence of transformation-reconfiguration-substitution-de-alignment/re-alingment.

Various obstacles are associated with the dynamics of the high niche-demanding pathways, which may interrupt a timely transition, typically by 'clogging' the transition at the take-off phase. Typical of these obstacles are the low cost performance factor associated with HFCV and high initial purchase price and inadequate infrastructure are main obstacles to the adoption of the BEV. The best way to overcome these challenges and keep the transition going is through provision of an environment of natural transition rather than dictates from the government in a top-down manner. This can be done by widening vehicle technology options and making their choice attractive through affordability and reliability by government. Thus, the government although cannot make transitions happen on its own, can play crucial role in support of the transition process. Government roles shall include areas like support for niche technology developments, raising public awareness on the risks of over-reliance on unstable energy sources and their global warming consequence and need for a radical and urgent shift to sustainable options, while maintaining the principle of reflexive governance.

8.3 The transition prospect of UK power generation sector

In chapter 6, numerical measurements are designed and used for elements of the three levels of the multi-level perspective framework namely; landscape pressure (P_L), niche pressure (P_n) and regime resistance (R_r) to study transition processes. A trend of transition momentum M_t is derived from the three transition components using the UK's 'dash for gas' transition. It has been shown that the pre-development phase to a regime change pathway occurs at M_t = 0.35k, the cracking point of regimes or the take-off phase at M_t = 1.0k, the breakthrough or acceleration phase at M_t = 1.80k, the stabilisation phase at M_t = 3.7k whereas the meeting point for the old and new regime technologies occurs at M_t = 3.4k. This may also stand for the mid-point of the acceleration phase. For transformation that does not involve regime discontinuity, the pathway occurs before M_t reaches the regime breaking point, i.e. $M_t < 1.0k$. These M_t values have been related to the ongoing transition of UK's fossil fuel power regime and some important conclusions are derived.

The period between 1980 and 2000 has been characterised by a transformation pathway transition of fossil fuel power regime (the dash for gas transition appeared as a transformation on the larger regime). Similarly, the landscape effect as at year 2000 did not diminish but maintained a medium magnitude corresponding with moderate niche performance, i.e. $\mathrm{mP_L}$: $\mathrm{mP_n}$. This results in another transformation process throughout the first decade of the 21st century. However, although P_L values remain medium up till the late 2010s, the actual impact on the regime was perceived as high since the late 2000s due to the imminent irreversible high $P_{L/co2}$ effects as envisaged by the IPCC. This results in a combination of (h)$\mathrm{P_L}$: $\mathrm{hP_n}$ which means a substitution scenario; the transformation transition may be said to have metamorphosed to a pre-development phase of a substitution pathway. Therefore, the period between 2000 and 2012 may be said to have been characterised by transformation process and/or pre-development phase to substitution transition.

The regime did not crack until around 2013, where $M_{t/ff \rightarrow ren}$ = 1.0k. This development created an opportunity for the take-off phase. Several cracks may be identified in the fossil fuel regime although it continued to occupy the dominant position in the power generation sector. An important crack in the regime is the increased awareness by regime actors (policy makers and investors) of the environmental consequence of conventional fossil fuel power plants and their reluctance to promote their developments. A second crack is the intensified commitments to the European Union emissions trading scheme (ETS) which integrates a cost for carbon emissions. A third crack is the emphasis on energy efficiency and energy conservation which requires energy users to reduce demand and make optimum use of available electricity energy. The early 2010s witnessed a rise in $M_{t/ff \rightarrow ren}$ as a result. This upsurge was accompanied by a similar and unprecedented development in renewable electricity, a development that is in line with a take-off phase.

According to the $M_{t/ff \rightarrow ren}$ trend, starting points of the acceleration phase of the transition to renewables should be expected around the early 2020s. The mid-acceleration and stabilisation are not far apart and may be expected around the mid-2020s. The transition is expected to end before the mid-2030s. The resulting dominant renewable energy regime will take the form of a distributed generation due to a multi-direction investment in various renewable electricity technologies owing to the similarity in P_n factor among the alternatives. Considering lower level regimes of individual technologies will suggest otherwise. At this level, the currently dominant gas CCGT technology may still maintain its position and another transition in the sector may become imperative. Prospective alternatives are technologies under the three categories of renewables, CCS and nuclear (new generation).

More prospective power options in the UK will no doubt include those with low/medium operation risk, high and increasing performance such as biomass, wind (both onshore and offshore), and solar PV. So far, the levels of investment trends/potentials in these technology options are similar and indicate a high uncertainty in a single investment direction. And in addition to the current fast growing landscape pressure (especially beyond year 2020), there are strong indications that the most likely pathway scenario in the UK power sector at the lower regime level will be the de-alignment/re-alignment. This pathway will result in a systemic transformation in the infrastructural and institutional arrangements of UK power sector regime. Under this scenario, conventional coal, oil and gas power sources will seize to exist owing to the very high P_L magnitude of above 0.8 toward year 2030. This event will give way to experiments and competition among currently leading and prospective alternatives such as wind, biomass, solar PV (and also nuclear EPWR which must have attained investment consideration). The power industry will be characterised by loosely coupled grid islands located close to consumers. This will necessitate bidirectional flows of electricity energy in order to maintain a balance between demand and supply. A typical technical requirement will therefore be the integration of smart grids for a smooth operation.

8.4 Overall carbon performance in the UK

This thesis attempts to assess the transition merits of the United Kingdom using some recent ideas in transitions theory to help better understand the possible shape of its future decarbonisation pathways. Therefore, it is a descriptive and exploratory work that applies transition pathway theory to analyse the effects of the various pathways on the UK energy portfolio. It is clear that the UK is very likely to meet its greenhouse gas reduction targets under the Kyoto Protocol. The impressive progress of the UK in reducing emissions is directly related to its implementation of more effective policies and measures including economic incentives and disincentives, energy and carbon taxes, major investments in renewable energy and energy efficiency, and regulations. Also, greater analytical tools for transitions such as modulation are required, with specific reference to decarbonisation and sustainability assessments.

8.5 Further work

In this research work, an attempt has been made to design a graphical representation of socio-technical transition pathways to reveal their likely sequence. The sequence depends on the rates of changes of P_L and γ_n as well as the $P_{Lt.D/R} - P_{Lt.R}$ and $\gamma_{n.S} - \gamma_{n.R}$ differences. However, it is necessary to establish fairly precise measurements for P_L and γ_n for all the pathways including their rates of change to give a modest conclusion on a clear status of the pathways and the sequence especially in terms of D/R and S positions. Also formulation of numerical values of and relationships between landscape pressure P_L, niche maturity γ_n and regime transition τ for the pathways is important for a clear understanding of their dynamics and sequence. Adequate knowledge on pathway dynamics and sequence help to easily identify a likely scenario when a disruptive landscape pressure is imminent and subsequently, its suitability and performance in terms of the goals of transition. Such insights help in guiding transitions in the most efficient way by designing relevant and timely precautionary measures.

Further work on this research direction should also involve comprehensive considerations in designing measurements for developments on the socio-technical landscape level of the MLP. This work only considers concentrations of harmful atmospheric gases at the landscape level. In reality, factors that constitute elements at the landscape level are beyond the natural environment and are heterogeneous and complex. These factors include macroeconomic factors such oil prices, economic growth, broad political coalitions, social patterns, worldviews and paradigms, wars, etc. Ideally, a more accurate measurement of landscape pressure should consider such factors that may occur at any given time. For instance, similar to harmful emissions concentrations, P_L due to oil price changes may suitably be measured by defining an upper and lower boundary for international oil price based on fuel price experience. However, unlike the P_L due to emissions concentrations whose changes are a direct result of the causer activities, such economic P_L developments are far beyond the direct influence of its causer and are highly unpredictable. This situation will warrant greater deal of considerations and efforts in developing measurement tools that can give a fair numerical representation thereof.

Such considerations will call for a painstaking analysis of current and future rates of energy demands due to changes in GDP, population, energy intensity, rates of energy production due to availability of production fields and resource, speculations and fear about energy security as a result of social, political and economic changes, etc. Exclusion of any landscape element may reflect an incomplete assessment of P_L and hence a compromised result of a transition! This implies that the current findings relating to future transition pathways and institutional/infrastructural changes in this research work are subject to deviations from expected patterns when other landscape factors make influences.

Appendices

Appendix A. The Kyoto Protocol to the UNFCCC

Table A1. List of parties and signatories to the Kyoto protocol to the UNFCCC

S/ No	Participant	Signature	Ratification Acceptance (A) Accession (a) Approval (AA)	Entry into force
1	Afghanistan		25 March 2013 a	23 June 2013
2	Albania		1 Apr 2005 a	30 Jun 2005
3	Algeria		16 Feb 2005 a	17 May 2005
4	Andorra		2 Mar 2011 a	31 May 2011
5	Angola		8 May 2007 a	6 Aug 2007
6	Antigua and Barbuda	16 Mar 1998	3 Nov 1998	16 Feb 2005
7	Argentina	16 Mar 1998	28 Sep 2001	16 Feb 2005
8	Armenia		25 Apr 2003 a	16 Feb 2005
9	Australia*	29 Apr 1998	12 Dec 2007	11 Mar 2008
10	Austria*	29 Apr 1998	31 May 2002	16 Feb 2005
11	Azerbaijan	12 Jun 1992	16 May 1995	14 Aug 1995
12	Bahamas		9 Apr 1999 a	16 Feb 2005
13	Bahrain		31 Jan 2006 a	1 May 2006
14	Bangladesh		22 Oct 2001 a	16 Feb 2005
15	Barbados		7 Aug 2000 a	16 Feb 2005
16	Belarus*		26 Aug 2005 a	24 Nov 2005
17	Belgium*	29 Apr 1998	31 May 2002	16 Feb 2005
18	Belize		26 Sep 2003 a	16 Feb 2005
19	Benin		25 Feb 2002 a	16 Feb 2005
20	Bhutan		26 Aug 2002 a	16 Feb 2005
21	Bolivia	9 Jul 1998	30 Nov 1999	16 Feb 2005
22	Bosnia and Herzegovina		16 Apr 2007 a	15 Jul 2007
23	Botswana		8 Aug 2003 a	16 Feb 2005
24	Brazil	29 Apr 1998	23 Aug 2002	16 Feb 2005
25	Brunei Darussalam		20 Aug 2009 a	18 Nov 2009
26	Bulgaria*	18 Sep 1998	15 Aug 2002	16 Feb 2005
27	Burkina Faso		31 Mar 2005 a	29 Jun 2005
28	Burundi		18 Oct 2001 a	16 Feb 2005
29	Cabo Verde		10 Feb 2006 a	11 May 2006
30	Cambodia		22 Aug 2002 a	16 Feb 2005
31	Cameroon		28 Aug 2002 a	16 Feb 2005
32	Canada* *(w)*	[29 Apr 1998]	[17 Dec 2002]	16 Feb 2005 [15 Dec 2012 w]
33	Central African Republic		18 Mar 2008 a	16 Jun 2008
34	Chad		18 Aug 2009 a	17 Nov 2009

Source: UNFCCC (2014f)

Table A1 cont’d

35	Chile	17 Jun 1998	26 Aug 2002	16 Feb 2005
36	China	29 May 1998	30 Aug 2002 AA	16 Feb 2005
37	Colombia		30 Nov 2001 a	16 Feb 2005
38	Comoros		10 Apr 2008 a	9 Jul 2008
39	Congo		12 Feb 2007 a	13 May 2007
40	Cook islands	16 Sep 1998	27 Aug 2001	16 Feb 2005
41	Costa Rica	27 Apr 1998	9 Aug 2002	16 Feb 2005
42	Cote D'ivoire		23 Apr 2007 a	22 Jul 2007
43	Croatia*	11 Mar 1999	30 May 2007	28 Aug 2007
44	Cuba	15 Mar 1999	30 Apr 2002	16 Feb 2005
45	Cyprus		16 Jul 1999 a	16 Feb 2005
46	Czech republic*	23 Nov 1998	15 Nov 2001 AA	16 Feb 2005
47	Democratic People's Republic of Korea		27 Apr 2005 a	26 Jul 2005
48	Democratic Republic of Congo		23 Mar 2005 a	21 Jun 2005
49	Denmark*	29 Apr 1998	31 May 2002 *(3)*	16 Feb 2005
50	Djibouti		12 Mar 2002 a	16 Feb 2005
51	Dominica		25 Jan 2005 a	25 Apr 2005
52	Dominican republic		12 Feb 2002 a	16 Feb 2005
53	Ecuador	15 Jan 1999	13 Jan 2000	16 Feb 2005
54	Egypt	15 Mar 1999	12 Jan 2005	12 Apr 2005
55	El Salvador	8 Jun 1998	30 Nov 1998	16 Feb 2005
56	Equatorial Guinea		16 Aug 2000 a	16 Feb 2005
57	Eritrea		28 Jul 2005 a	26 Oct 2005
58	Estonia*	3 Dec 1998	14 Oct 2002	16 Feb 2005
59	Ethiopia		14 Apr 2005 a	13 Jul 2005
60	European union*	29 Apr 1998	31 May 2002 AA	16 Feb 2005
61	Fiji	17 Sep 1998	17 Sep 1998	16 Feb 2005
62	Finland*	29 Apr 1998	31 May 2002	16 Feb 2005
63	France*	29 Apr 1998	31 May 2002 AA	16 Feb 2005
64	Gabon		12 Dec 2006 a	12 Mar 2007
65	Gambia		1 Jun 2001 a	16 Feb 2005
66	Georgia		16 Jun 1999 a	16 Feb 2005
67	Germany*	29 Apr 1998	31 May 2002	16 Feb 2005
68	Ghana		30 May 2003 a	16 Feb 2005
69	Greece*	29 Apr 1998	31 May 2002	16 Feb 2005
70	Grenada		6 Aug 2002 a	16 Feb 2005
71	Guatemala	10 Jul 1998	5 Oct 1999	16 Feb 2005
72	Guinea		7 Sep 2000 a	16 Feb 2005
73	Guinea-Bissau		18 Nov 2005 a	16 Feb 2005
74	Guyana		5 Aug 2003 a	16 Feb 2005
75	Haiti		6 Jul 2005 a	4 Oct 2005
76	Honduras	25 Feb 1999	19 Jul 2000	16 Feb 2005
77	Hungary*		21 Aug 2002 a	16 Feb 2005

Source: UNFCCC (2014f)

Table A1 cont'd

78	Iceland*		23 May 2002 a	16 Feb 2005
79	India		26 Aug 2002 a	16 Feb 2005
80	Indonesia	13 Jul 1998	3 Dec 2004	3 Mar 2005
81	Iran (Islamic Rep. of)		22 Aug 2005 a	20 Dec 2005
82	Iraq		28 Jul 2009 a	26 Oct 2009
83	Ireland*	29 Apr 1998	31 May 2002	16 Feb 2005
84	Israel	16 Dec 1998	15 Mar 2004	16 Feb 2005
85	Italy*	29 Apr 1998	31 May 2002	16 Feb 2005
86	Jamaica		28 Jun 1999 a	16 Feb 2005
87	Japan*	28 Apr 1998	4 Jun 2002 A	16 Feb 2005
88	Jordan		17 Jan 2003 a	16 Feb 2005
89	Kazakhstan**	12 Mar 1999	19 Jun 2009	17 Sep 2009
90	Kenya		25 Feb 2005 a	26 May 2005
91	Kiribati		7 Sep 2000 a	16 Feb 2005
92	Kuwait		11 Mar 2005 a	9 Jun 2005
93	Kyrgyzstan		13 May 2003 a	16 Feb 2005
94	Lao people's Democratic Republic		6 Feb 2003 a	16 Feb 2005
95	Latvia*	14 Dec 1998	5 Jul 2002	16 Feb 2005
96	Lebanon		13 Nov 2006 a	11 Feb 2007
97	Lesotho		6 Sep 2000 a	16 Feb 2005
98	Liberia		5 Nov 2002 a	16 Feb 2005
99	Libya		24 Aug 2006 a	22 Nov 2006
100	Liechtenstein*	29 Jun 1998	3 Dec 2004	3 Mar 2005
101	Lithuania*	21 Sep 1998	3 Jan 2003	16 Feb 2005
102	Luxembourg*	29 Apr 1998	31 May 2002	16 Feb 2005
103	Madagascar		24 Sep 2003 a	16 Feb 2005
104	Malawi		26 Oct 2001 a	16 Feb 2005
105	Malaysia	12 Mar 1999	4 Sep 2002	16 Feb 2005
106	Maldives	16 Mar 1998	30 Dec 1998	16 Feb 2005
107	Mali	27 Jan 1999	28 Mar 2002	16 Feb 2005
108	Malta*	17 Apr 1998	11 Nov 2001	16 Feb 2005
109	Marshall islands	17 Mar 1998	11 Aug 2003	16 Feb 2005
110	Mauritania		22 Jul 2005 a	20 Oct 2005
111	Mauritius		9 May 2001 a	16 Feb 2005
112	Mexico	9 Jun 1998	7 Sep 2000	16 Feb 2005
113	Micronesia	17 Mar 1998	21 Jun 1999	16 Feb 2005
114	Monaco*	29 Apr 1998	27 Feb 2006	28 May 2006
115	Mongolia		15 Dec 1999 a	16 Feb 2005
116	Montenegro		4 Jun 2007 a	2 Sep 2007
117	Morocco		25 Jan 2002 a	16 Feb 2005
118	Mozambique		18 Jan 2005 a	18 Apr 2005
119	Myanmar		13 Aug 2003 a	16 Feb 2005

Source: UNFCCC (2014f)

Table A1 cont'd

120	Namibia		4 Sep 2003 a	16 Feb 2005
121	Nauru		16 Aug 2001 a	16 Feb 2005
122	Nepal		16 Sep 2005 a	15 Dec 2005
123	Netherlands*	29 Apr 1998	31 May 2002 A	16 Feb 2005
124	New Zealand*	22 May 1998	19 Dec 2002 *(5)*	16 Feb 2005
125	Nicaragua	7 Jul 1998	18 Nov 1999	16 Feb 2005
126	Niger	23 Oct 1998	30 Sep 2004	16 Feb 2005
127	Nigeria		10 Dec 2004 a	10 Mar 2005
128	Niue	8 Dec 1998	6 May 1999	16 Feb 2005
129	Norway*	29 Apr 1998	30 May 2002	16 Feb 2005
130	Oman		19 Jan 2005 a	19 Apr 2005
131	Pakistan		11 Jan 2005 a	11 Apr 2005
132	Palau		10 Dec 1999 a	16 Feb 2005
133	Panama	8 Jun 1998	5 Mar 1999	16 Feb 2005
134	Papua new guinea	2 Mar 1999	28 Mar 2002	16 Feb 2005
135	Paraguay	25 Aug 1998	27 Aug 1999	16 Feb 2005
136	Peru	13 Nov 1998	12 Sep 2002	16 Feb 2005
137	Philippines	15 Apr 1998	20 Nov 2003	16 Feb 2005
138	Poland*	15 Jul 1998	13 Dec 2002	16 Feb 2005
139	Portugal*	29 Apr 1998	31 May 2002 AA	16 Feb 2005
140	Qatar		11 Jan 2005 a	11 Apr 2005
141	Republic of Korea	25 Sep 1998	8 Nov 2002	16 Feb 2005
142	Republic of Moldova		22 Apr 2003 a	16 Feb 2005
143	Romania*	5 Jan 1999	19 Mar 2001	16 Feb 2005
144	Russian Federation*	11 Mar 1999	18 Nov 2004	16 Feb 2005
145	Rwanda		22 Jul 2004 a	16 Feb 2005
146	Saint Kitts and Nevis		8 Apr 2008 a	7 Jul 2008
147	Saint Lucia	16 Mar 1998	20 Aug 2003	16 Feb 2005
148	Saint Vincent and the Grenadines	19 Mar 1998	31 Dec 2004	31 Mar 2005
149	Samoa	16 Mar 1998	27 Nov 2000	16 Feb 2005
150	San Marino		28 April 2010	27 Jul 2010
151	Sao Tome and Principe		25 Apr 2008 a	24 Jul 2008
152	Saudi Arabia		31 Jan 2005 a	1 May 2005
153	Senegal		20 Jul 2001 a	16 Feb 2005
154	Serbia		19 Oct 2007 a	17 Jan 2008
155	Seychelles	20 Mar 1998	22 Jul 2002	16 Feb 2005
156	Sierra Leone		10 Nov 2006 a	8 Feb 2007
157	Singapore		12 Apr 2006 a	11 Jul 2006
158	Slovakia*	26 Feb 1999	31 May 2002	16 Feb 2005
159	Slovenia*	21 Oct 1998	2 Aug 2002	16 Feb 2005
160	Solomon Islands	29 Sep 1998	13 Mar 2003	16 Feb 2005
161	Somalia		26 July 2010	24 Oct 2010

Source: UNFCCC (2014f)

Table A1 cont'd

162	South Africa		31 Jul 2002 a	16 Feb 2005
163	Spain*	29 Apr 1998	31 May 2002	16 Feb 2005
164	Sri Lanka		3 Sep 2002 a	16 Feb 2005
165	Sudan		2 Nov 2004 a	16 Feb 2005
166	Suriname		25 Sep 2006 a	24 Dec 2006
167	Swaziland		13 Jan 2006 a	13 Apr 2006
168	Sweden*	29 Apr 1998	31 May 2002	16 Feb 2005
169	Switzerland*	16 Mar 1998	9 Jul 2003	16 Feb 2005
170	Syrian Arab Republic		27 Jan 2006 a	27 Apr 2006
171	Tajikistan		29 Dec 2008 a	29 Mar 2009
172	Thailand	2 Feb 1999	28 Aug 2002	16 Feb 2005
173	The Former Yugoslav Republic of Macedonia		18 Nov 2004 a	16 Feb 2005
174	Timor-Leste		14 Oct 2008 a	12 Jan 2009
175	Togo		2 Jul 2004 a	16 Feb 2005
176	Tonga		14 Jan 2008 a	13 Apr 2008
177	Trinidad and Tobago	7 Jan 1999	28 Jan 1999	16 Feb 2005
178	Tunisia		22 Jan 2003 a	16 Feb 2005
179	Turkey*		28 May 2009 a	26 Aug 2009
180	Turkmenistan	28 Sep 1998	11 Jan 1999	16 Feb 2005
181	Tuvalu	16 Nov 1998	16 Nov 1998	16 Feb 2005
182	Uganda		25 Mar 2002 a	16 Feb 2005
183	Ukraine*	15 Mar 1999	12 Apr 2004	16 Feb 2005
184	United Arab Emirates		26 Jan 2005 a	26 Apr 2005
185	United Kingdom of Great Britain and Northern Ireland*	29 Apr 1998	31 May 2002	16 Feb 2005
186	United Republic of Tanzania		26 Aug 2002 a	16 Feb 2005
187	United states of America*	12 Nov 1998		
188	Uruguay	29 Jul 1998	5 Feb 2001	16 Feb 2005
189	Uzbekistan	20 Nov 1998	12 Oct 1999	16 Feb 2005
190	Vanuatu		17 Jul 2001 a	16 Feb 2005
191	Venezuela		18 Feb 2005 a	19 May 2005
192	Viet Nam	3 Dec 1998	25 Sep 2002	16 Feb 2005
193	Yemen		15 Sep 2004 a	16 Feb 2005
194	Zambia	5 Aug 1998	7 Jul 2006	5 Oct 2006
195	Zimbabwe		30 Jun 2009 a	28 Sep 2009

Source: UNFCCC (2014f)

Notes: 1) There are 192 parties and 83 signatories; 2) * indicates an Annex I Party to the UNFCCC; 3) ** indicates an Annex I Party for the purposes of the Kyoto Protocol; 4) The dates in the third column are those of the receipt of the instrument of ratification, acceptance (A), approval (AA) or accession (a); 5) "w" indicates withdrawal

Table A2. List of annex I parties to the convention with some of their important features

Participant (UNFCCC, 2014g)	**CO2 Emission mton, (2012)** (EIA, n.d.)	**Quantified Emission Limitation/Reduction Commitment (% of base yr)** (UNFCCC, n.d.)			**Emission Reduction Scheme Name** (Parliament of Australia, 2013)	**GDP per capita** (Central Intelligence Agency, n.d.)
		2008-2012	2013-2017	2018-2022		
Australia*	420.633	108	71	51	EU ETS	$42,400
Austria*	66.675	92	49	15	EU ETS	$42,500
Belarus	67.126	92	95	91	EU ETS	$16,000
Belgium*	139.139	92	50	17	EU ETS	$38,100
Bulgaria	48.848	92	94	90	EU ETS	$14,200
Canada*	550.829	94	65	42		$41,500
Croatia	20.179	95	87	78	EU ETS	$18,100
Cyprus	8.801				EU ETS	$26,900
Czech Republic	91.155	92	79	65	EU ETS	$27,200
Denmark*	40.512	92	59	31	EU ETS	$37,700
Estonia	5.686	92	91	84	EU ETS	$21,200
European Union*	*4,370.29*	92	63	38	EU ETS	$34,500
Finland*	46.81	92	67	45	EU ETS	$36,500
France*	364.538	92	48	14	EU ETS	$35,500
Germany*	788.321	92	60	33	EU ETS	$39,100
Greece*	87.558	92	70	51	EU ETS	$25,100
Hungary	47.903	94	81	69	EU ETS	$19,800
Iceland*	3.505	110	61	35	Linked to EU ETS	$39,400
Ireland*	35.489	92	64	41	EU ETS	$41,700
Italy*	385.813	92	65	42	EU ETS	$30,100
Japan*	1259.058	94	62	36	Metropolitan & Provincial ETS	$36,200
Latvia	7.897	92	88	81	EU ETS	$18,100
Liechtenstein		92	63	38	Linked to EU ETS	$89,400
Lithuania	16.689	92	89	82	EU ETS	$20,100
Luxembourg*	11.687	92	55	25	EU ETS	$80,700
Malta	6.564				EU ETS	$26,100
Monaco		92	63	38		$70,700
Netherlands*	239.605	92	62	36	EU ETS	$42,300
New Zealand*	37.889	100	73	55	New Zealand ETS	$28,800
Norway*	41.058	101	45	8	Linked to EU ETS	$55,300

Table A2 cont'd

Poland	289.455	94	83	72	EU ETS	$21,000
Portugal*	51.196	92	73	55	EU ETS	$23,000
Romania	86.058	92	93	89	EU ETS	$12,800
Russian Fed.	1781.72	100	93	88		$17,700
Slovakia	32.080	92	84	74	EU ETS	$24,300
Slovenia	15.872	92	72	53	EU ETS	$28,600
Spain*	312.442	92	58	30	EU ETS	$30,400
Sweden*	51.077	92	42	4	EU ETS	$41,700
Switzerland*	42.966	92	48	14	Swiss ETS, planned link to EU ETS	$54,600
Turkey	296.932		92	86		$15,000
Ukraine	290.38	100	98	97		$7,600
United Kingdom*	498.877	92	44	6	EU ETS	$36,700
United States of America*	5270.422	93	61	34		49,800

Notes:
1) Annex I parties are industrialised countries (actually developed countries) with a binding commitment in the Annex B of the Kyoto Protocol which sets binding targets for each of industrialised countries in percentage of their base year emission (1990);
2) Annex I Parties with the base year other than 1990 are Bulgaria (1988), Hungary (average of 1985-1987), Poland (1988), Romania (1989), Slovenia (1986);
3) Annex II parties are developed countries providing financial resources and transfer of technology through the adaptation fund for climate change (2% of CERs issued for a CDM project activity) for minimizing impacts on developing countries;
4) ***** also annex II party;

Table A3. List of non-annex I parties to the UNFCCC with some of their features

Participant (UNFCCC, 2014g)	**Annual CO2 Emission mton, (2012)** EIA (n.d.)	**Quantified Emission Limitation/Reduction Commitment (2008-2022) (% of base yr)** (UNFCCC, n.d.)	**Emission Reduction Scheme** (UNFCCC, 2014h)	**GDP per capita (2012)** (Central Intelligence Agency, n.d.)
Afghanistan	8.552	-	Programmes	$1,000
Albania	3.962	-	Programmes	$8,000
Algeria	133.921	-	Programmes	$7,500
Andorra		-	Programmes	$37,200
Angola	31.614	-	Programmes	$6,200
Antigua & Barbuda	0.586	-	Programmes	$17,500
Argentina	195.999	-	Programmes	$18,200
Armenia**	12.118	-	Programmes	$5,600
Azerbaijan	35.140	-	Programmes	$10,700
Bahamas	3.836	-	Programmes	$31,300
Bahrain	32.200	-	Programmes	$28,200
Bangladesh	63.497	-	Programmes	$2,000
Barbados	1.312	-	Programmes	$25,500
Belize	0.675	-	Programmes	$8,400
Benin	4.581	-	Programmes	$1,700
Bhutan	0.321	-	Programmes	$6,500
Bolivia	17.28493	-	Programmes	$5,000
Bosnia and Herzegovina	25.997	-	Programmes	$8,300
Botswana	3.919	-	Programmes	$16,800
Brazil	500.229	-	Programmes	$12,000
Brunei Darussalam	8.678	-	Programmes	$50,500
Burkina Faso	1.406	-	Programmes	$1,400
Burundi	0.315	-	Programmes	$600
Cambodia	6.055	-	Programmes	$2,400
Cameroon	6.224	-	Programmes	$2,300
Cape Verde	0.386	-	Programmes	$4,100
Central African Republic	0.435	-	Programmes	$800
Chad	0.264	-	Programmes	$2,000
Chile	81.506	-	Programmes	$18,400
China	8106.43	-	Programmes	$9,100
Columbia	74.896	-	Programmes	$10,700
Comoros	0.157	-	Programmes	$1,300
Congo	6.691	-	Programmes	$4,700
Cook Islands	0.150	-	Programmes	$9,100

Table A3 cont'd

Costa Rica	7.290	-	Programmes	$12,600
Cuba	25.987	-	Programmes	$9,900
Côte d'Ivoire	6.403	-	Programmes	$1,700
Democratic People's Rep. of Korea (N.K)	67.001	-	Programmes	$1,800
Democratic Rep. of the Congo	2.481	-	Programmes	$400
Djibouti	1.796	-	Programmes	$2,700
Dominica	0.132	-	Programmes	$14,600
Dominican Republic	20.796	-	Programmes	$9,600
Ecuador	37.23169	-	Programmes	$8,800
Egypt	206.293	-	Programmes	$6,600
El Salvador	6.37496	-	Programmes	$7,700
Equatorial Guinea	5.614	-	Programmes	$20,200
Eritrea	0.74	-	Programmes	$800
Ethiopia	8.213	-	Programmes	$1,200
Fiji	1.543	-	Programmes	$4,800
Gabon	5.437	-	Programmes	$17,300
Gambia	0.472	-	Programmes	$1,900
Georgia	6.258	-	Programmes	$5,900
Ghana	9.098	-	Programmes	$3,300
Grenada	0.431	-	Programmes	$14,100
Guatemala	13.069	-	Programmes	$5,200
Guinea	1.388	-	Programmes	$1,100
Guinea-Bissau	0.460	-	Programmes	$1,100
Guyana	1.661	-	Programmes	$8,000
Haiti	2.094	-	Programmes	$1,300
Honduras	10.331	-	Programmes	$4,600
India	1830.938	-	Programmes	$3,900
Indonesia	456.210	-	Programmes	$5,000
Iran (Islamic Republic of)	603.586	-	Programmes	$13,100
Iraq	130.742	-	Programmes	$4,600
Israel	80.358	-	Programmes	$32,200
Jamaica	12.751	-	Programmes	$9,100
Jordan	16.855	-	Programmes	$6,000
Kazakhstan**	224.22	-	Programmes	$13,900
Kenya	13.446	-	Programmes	$1,800
Kiribati	0.0585	-	Programmes	$5,900
Kuwait	105.684	-	Programmes	$43,800
Kyrgyzstan	9.278	-	Programmes	$2,400

Table A3 cont'd

Lao People's Democratic Republic	1.623	-	Programmes	$3,000
Lebanon	16.441	-	Programmes	$15,900
Lesotho	0.270	-	Programmes	$2,000
Liberia	0.542	-	Programmes	$700
Libya	54.600	-	Programmes	$13,300
Madagascar	2.886	-	Programmes	$1,000
Malawi	1.910	-	Programmes	$900
Malaysia	198.785	-	Programmes	$16,900
Maldives	1.123	-	Programmes	$8,700
Mali	0.774	-	Programmes	$1,100
Marshall Islands		-	Programmes	$2,500
Mauritania	2.408	-	Programmes	$2,100
Mauritius	5.317	-	Programmes	$15,600
Mexico	453.833	-	Programmes	$15,300
Micronesia (Federated States of)		-	Programmes	$2,200
Mongolia	11.365	-	Programmes	$5,400
Montenegro	19.718	-	Programmes	$11,700
Morocco	39.349	-	Programmes	$5,300
Mozambique	4.789	-	Programmes	$1,200
Myanmar	13.341	-	Programmes	$1,400
Namibia	3.716	-	Programmes	$7,800
Nauru	0.169	-	Programmes	$5,000
Nepal	3.638	-	Programmes	$1,300
Nicaragua	5.285	-	Programmes	$3,300
Niger	1.411	-	Programmes	$900
Nigeria	86.398	-	Programmes	$2,700
Niue	0.004	-	Programmes	$5,800
Oman	62.853	-	Programmes	$28,500
Pakistan	146.889	-	Programmes	$2,900
Palau		-	Programmes	$8,100
Palestine*	*2.502*	-	Programmes	
Panama	16.228	-	Programmes	$15,300
Papua New Guinea	3.385	-	Programmes	$2,700
Paraguay	3.869	-	Programmes	$6,100
Peru	53.582	-	Programmes	$10,700
Philippines	83.95	-	Programmes	$4,300
Qatar	99.165	-	Programmes	$102,800
Republic of Korea (S.K.)	657.093	-	Programmes	$32,400

Table A3 cont’d

Republic of Moldova**	9.415	-	Programmes	$3,500
Rwanda	0.769	-	Programmes	$1,400
Saint Kitts and Nevis	0.251	-	Programmes	$15,500
Saint Lucia	0.416	-	Programmes	$13,300
Saint Vincent and the Grenadines	0.269	-	Programmes	$11,900
Samoa	0.161	-	Programmes	$6,200
San Marino		-	Programmes	$36,200
Sao Tome and Principe	0.138	-	Programmes	$2,300
Saudi Arabia	582.670	-	Programmes	$25,700
Senegal	7.139	-	Programmes	$1,900
Serbia	41.376	-	Programmes	$10,500
Seychelles	1.304	-	Programmes	$26,200
Sierra Leone	1.311	-	Programmes	$1,400
Singapore	207.960	-	Programmes	$60,900
Solomon Islands	0.266	-	Programmes	$3,400
South Africa	473.165	-	Programmes	$11,300
South Sudan (and Sudan)	13.943	-	Programmes	$900
Sri Lanka	15.235	-	Programmes	$6,100
Sudan (and South Sudan)	13.943	-	Programmes	$2,400
Suriname	2.268	-	Programmes	$12,300
Swaziland	0.937	-	Programmes	$5,300
Syrian Arab Republic	50.922	-	Programmes	$5,100
Tajikistan	2.973	-	Programmes	$2,200
Thailand	290.717	-	Programmes	$10,000
The former Yugoslav Rep. of Macedonia	8.084	-	Programmes	$10,700
Timor-Leste	0.496	-	Programmes	$9,500
Togo	1.63	-	Programmes	$1,100
Tonga	0.189	-	Programmes	$7,500
Trinidad and Tobago	51.267	-	Programmes	$20,400
Tunisia	20.273	-	Programmes	$9,700
Turkmenistan**	64.979	-	Programmes	$8,500
Tuvalu		-	Programmes	$3,300
Uganda	2.548	-	Programmes	$1,400

Table A3 cont'd

United Arab Emirates	234.060	-	Programmes	$49,000
United Rep. of Tanzania	9.295	-	Programmes	$1,700
Uruguay	7.591	-	Programmes	$15,800
Uzbekistan**	123.170	-	Programmes	$3,500
Vanuatu	0.166	-	Programmes	$4,900
Venezuela (Bolivarian Republic of)	184.793	-	Programmes	$13,200
Viet Nam	131.732	-	Programmes	$3,500
Yemen	21.279	-	Programmes	$2,200
Zambia	3.054	-	Programmes	$1,700
Zimbabwe	10.116	-	Programmes	$500

Notes: 1) *Observer state; 2) **Party for which there is a specific COP (Conference of the Parties) and/or CMP (Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol) decision.

Appendix B. Low carbon energy policy in the UK

Table B1. Renewables energy policy

Policy	Description
UK Renewable Energy Roadmap	Sets out a plan for accelerating the use of onshore wind, offshore wind, marine energy, solar PV, biomass electricity and heat, ground source and air source heat pumps, and renewable transport
Renewables Obligation (RO)	provides incentives for large-scale renewable electricity generation by making UK suppliers source a proportion of their electricity from eligible renewable sources
Feed-in Tariffs (FITs) scheme	pays energy users who invest in small-scale, low-carbon electricity generation systems for the electricity they generate and use, and for unused electricity they export back to the grid
Renewable Heat Incentive (RHI)	pays commercial, industrial, public, not-for-profit and community generators of renewable heat for a 20-year period
Renewable Transport Fuel Obligation (RTFO)	makes companies that supply more than 450,000 litres of fuel per year source a percentage from renewable sources, support for other renewable technologies, eg heat networks
'Connect and manage network access regime' and other actions	to make sure new generators can connect to the electricity network in a timely, secure and cost-effective way

Source: DECC (2015)

Table B2. Nuclear energy policy

Policy	Description
National Policy Statements	Used to assess sites for potential new nuclear powers stations
Regulatory justification	A process to establish whether the benefits of new nuclear reactor designs outweigh the health risks
Waste and decommissioning arrangements	To make sure operators of new nuclear power stations put aside sufficient funds to pay for future decommissioning and waste disposal
Generic Design Assessment	used to assess the safety, security and environmental aspects of new reactor designs

Source: DECC (2015)

Table B3. Carbon capture and storage technology programme

Programme category	Description
Human capital	Running a competition (with £1 billion capital funding available) to support practical experience in the design, construction and operation of commercial-scale CCS
Finance	Funding a 4-year co-ordinated research, development and innovation programme
Investment/incentive	Working with industry to reduce costs of CCS technology, develop the supply chain, create storage and help develop CCS infrastructure

Source: DECC (2015)

Appendix C. Effects of meteorological variables on electricity generation technologies

Table C1. The effects of climate change and changing disaster risks on fossil fuel based electricity generation

Change in meteorological variable	**Impact on fossil fuel plant**	**Impact on electricity generation**
Temperature increase	Potential impact on water availability for cooling purposes.	Potentially decreased electricity generation due to limited water availability. Increased temperatures decrease the thermal generation efficiency of power plants.
Increase in average precipitation	None, unless flooding occurs. If flooding occurs risk of damage to power plant equipment.	None if no flooding occurs. If flooding occurs decreased electricity generation.
Decrease in average precipitation	Decreased availability of water for cooling purposes.	Decreased electricity generation.
Glacier melting	None, unless flooding occurs. If flooding occurs risk of damage to power plant equipment.	None if no flooding occurs. If flooding occurs decreased electricity generation.
Floods	Risk to power plant equipment and off shore equipment.	Decreased electricity generation if power plant or off shore equipment is flooded, destroyed or damaged.
Increased frequency and/or strength of storms/cyclones	Risk to power plant equipment and off shore equipment.	Decreased electricity generation if power plant or off shore equipment is destroyed or damaged.

Source: Urban & Mitchell (2011)

Table C2. The effects of climate change and changing disaster risks on nuclear electricity generation

Change in meteorological variable	**Impact on nuclear plant**	**Impact on electricity generation**
Temperature increase	Potential impact on water availability for cooling purposes.	Potentially decreased electricity generation due to limited water availability.
Increase in average precipitation	None, unless flooding occurs. If flooding occurs risk of damage to power plant equipment, potential health and safety implications.	None if no flooding occurs. If flooding occurs decreased electricity generation.
Decrease in average precipitation	Decreased availability of water for cooling purposes.	Decreased electricity generation.
Glacier melting	None, unless flooding occurs. If flooding occurs risk of damage to power plant equipment, potential serious health and safety implications.	None if no flooding occurs. If flooding occurs decreased electricity generation.
Floods	Risk to power plant equipment, potential health and safety implications.	Decreased electricity generation if power plant is flooded, destroyed or damaged.
Increased frequency and/or strength of storms/cyclones	Risk to power plant equipment, potential health and safety implications.	Decreased electricity generation if power plant is destroyed or damaged.

Source: Urban & Mitchell (2011)

Table C3. The effects of climate change and changing disaster risks on hydropower generation

Change in meteorological variable	**Impact on hydropower plant/ resources**	**Impact on electricity generation**
Temperature increase	Increased evaporation, reduced river run-off and lower water levels.	Decreased electricity generation.
Increase in average precipitation	Increased river run-off and higher water levels.	Increased electricity generation.
Decrease in average precipitation	Reduced river run-off and lower water levels.	Decreased electricity generation.
Droughts	Reduced river run-off and lower water levels.	Decreased electricity generation.
Glacier melting	Increased river run-off and higher water levels.	Increased electricity generation.
Floods	Increased river run-off and higher water levels. Flood gates are opened.	Increased electricity generation.
Increased frequency and/or strength of storms/cyclones	Risk to power plant equipment, reservoir and dam.	Decreased electricity generation if power plant, reservoir or dam is destroyed or damaged.

Source: Urban & Mitchell (2011)

Table C4. The effects of climate change and changing disaster risks on wind energy generation

Change in meteorological variable	**Impact on wind energy plant/ resources**	**Impact on electricity generation**
Temperature increase	Indirect impact on air density and wind patterns.	Either increased or decreased electricity generation possible.
Increase in average precipitation	None	None
Decrease in average precipitation	None	None
Droughts	None	None
Glacier melting	None, unless flooding occurs. If flooding occurs risk of damage to equipment.	None if no flooding occurs. If flooding occurs decreased electricity generation.
Floods	None, unless flooding occurs. If flooding occurs risk of damage to equipment.	None if no flooding occurs. If flooding occurs decreased electricity generation.
Increased frequency and/or strength of storms/cyclones	Risk to equipment	Decreased electricity generation if wind turbine is destroyed or damaged
Increased wind speeds	Better wind conditions	Increased electricity generations, unless a storm occurs
Decreased wind speeds	Worse wind conditions	Decreased electricity generation
Changes in wind patterns	Changes in air density, wind directions, wind variability	Either increased or decreased electricity generation possible

Source: Urban & Mitchell (2011)

Table C5. The effects of climate change and changing disaster risks on biomass-based electricity generation

Change in meteorological variable	**Impact on biomass-based power plant / resource**	**Impact on electricity generation**
Temperature increase	Potential impact on water availability for cooling purposes. Lower availability of biomass if plants reach threshold of biological heat tolerance or if sea level rise reduces the area where plants grow, otherwise there is an increase in biomass availability, increased fire risk.	Increased temperatures decrease the thermal generation efficiency of power plants. Either increased or decreased biomass availability on crop variety. Increased fire risk may jeopardise crop harvest.
Increase in average precipitation	Higher biomass availability if the precipitation increase occurs during the growing season.	Increased electricity generation.
Decrease in average precipitation	Lower biomass availability unless precipitation decrease occurs outside the growing season. Increased fire risk.	Decreased electricity generation, increased fire risk may jeopardise harvest.
Droughts	Lower biomass availability. Increased fire risk.	Decreased electricity generation, increased fire risk may jeopardise harvest.
Glacier melting	If under-irrigation of biomass resources: short to medium increase but long - term decrease depending on the situation of glaciers with regards to the current and future snow lines. Otherwise no changes.	As per availability.
Floods	Decreased availability of biomass resources if floods affect area where biomass is sourced.	Decreased electricity generation if power plant is flooded, destroyed or biomass availability is reduced.
Increased frequency and/or strength of storms/cyclones	Decreased availability of biomass resources if storms affect area where biomass is sourced.	Decreased electricity generation if power plant is flooded, destroyed or biomass availability is reduced.

Source: Urban & Mitchell (2011)

Table C6. The effects of climate change and changing disaster risks on solar based electricity generation

Change in meteorological variable	**Impact on solar power plant / resources**	**Impact on electricity generation**
Temperature increase	Better conditions if accompanied by increased solar radiation, lower cloud cover, worse conditions if accompanied with decreased solar radiation and higher cloud cover, otherwise unchanged.	Either increased, decreased or unchanged electricity generation possible. Increased temperatures decrease the thermal generation efficiency of power plants.
Increase in average precipitation	Worse conditions if accompanied with decreased solar radiation and higher cloud cover, otherwise unchanged.	Either decreased or unchanged electricity generation possible.
Decrease in average precipitation	Improved solar radiation and cloud cover.	Increased electricity generation.
Droughts	Higher solar radiation and lower cloud cover.	Decreased electricity generation.
Glacier melting	None, unless flooding occurs. If flooding occurs risk of damage to equipment.	None if no flooding occurs. If flooding occurs decreased electricity generation.
Floods	None, unless flooding occurs. If flooding occurs risk of damage to equipment.	None if no flooding occurs. If flooding occurs decreased electricity generation.
Increased frequency and/or strength of storms/cyclones	Risk to power plant equipment.	Decreased electricity generation if power plant is destroyed or damaged.
Increased solar radiation	Better solar conditions	Increased energy generation.
Decreased solar radiation	Worse solar conditions	Decreased energy generation
Changes in cloud cover	Better conditions if less cloud cover, worse conditions if more cloud cover.	Either increased or decreased energy generation possible.

Source: Urban & Mitchell (2011)

Appendix D. Energy consumption and GHG emissions in the UK

Table D1. The impact of energy efficiency on energy consumption and GHG emissions

Year	Energy use with EE measures (mtoe) (World Bank, 2014)	Energy intensity (koe/$1000 GDP) (constant 2011 PPP) (World Bank, 2014)	Energy use at constant 1990 energy intensity (mtoe) (World Bank, 2014)	GHG emissions with EE (mtco2eq) (UNFCCC, 2014c)	GHG intensity (kco2eq/ $1000 gdp) (UNFCCC, 2014c; World Bank, 2014)	GHG emissions at constant 1990 emissions intensity (mtco2eq) (UNFCCC, 2014c; World Bank, 2014)	Electric power consumption (TWh) (World Bank, 2014)
1990	205.92	150.35	205.92	783.41	572.00	783.41	306.65
1991	212.94	157.51	203.26	791.40	585.39	773.29	313.06
1992	212.21	154.97	205.89	769.63	562.02	783.30	313.95
1993	214.26	151.19	213.08	750.44	529.52	810.64	316.99
1994	215.79	145.08	223.63	740.05	497.54	850.79	311.33
1995	216.26	140.44	231.53	732.72	475.80	880.86	323.50
1996	225.58	141.54	239.62	754.56	473.46	911.61	338.29
1997	219.25	131.84	250.04	730.86	439.47	951.27	340.10
1998	221.48	128.59	258.96	730.80	424.30	985.20	345.59
1999	222.04	125.24	266.57	701.85	395.86	1014.15	352.53
2000	222.94	120.49	278.20	704.44	380.71	1058.39	360.1
2001	223.77	118.35	284.28	709.86	375.44	1081.51	363.11
2002	218.31	112.87	290.80	690.46	356.98	1106.34	364.70
2003	222.08	110.46	302.28	697.44	346.89	1150.03	368.30
2004	221.56	106.81	311.88	695.08	335.09	1186.52	368.25
2005	222.64	103.97	321.97	688.26	321.40	1224.90	378.78
2006	218.96	99.51	330.84	684.19	310.94	1258.65	377.28
2007	210.99	92.71	342.17	673.80	296.07	1301.78	374.22
2008	208.21	92.20	339.54	651.46	288.47	1291.77	371.82
2009	196.49	91.75	321.99	596.93	278.74	1224.98	351.44
2010	201.83	92.71	327.33	613.22	281.67	1245.31	357.78
2011	188.07	85.43	330.99	569.27	258.59	1259.22	346.16
2012	192.38	87.15	331.91	586.36	265.61	1262.719	351.00

Table D2. Final energy consumption and energy intensity

Year	Industry		Transport		Domestic	
	FEC (ktoe)	En. Int. (koe/ $05p)	FEC (ktoe)	En. Int. (koe/ $05p)	FEC (ktoe)	En. Int. (MWh/hh)
1990	38,660	0.100	48,635	0.031	40,756	4.139
1991	38,257		47,973		44,768	
1992	36,711		49,355		44,066	
1993	36,440		50,024		45,549	
1994	37,711		50,253		43,947	
1995	36,276		50,238		42,691	
1996	34,470		52,321		48,120	
1997	34,577		53,083		44,775	
1998	34,512		53,772		46,126	
1999	34,222		54,853		46,121	
2000	35,506	0.087	55,461	0.024	46,851	4.597
2001	35,443		55,137		48,178	
2002	33,764		55,685		47,471	
2003	34,074		56,366		48,293	
2004	32,912		57,374		49,333	
2005	32,303	0.077	58,793	0.021	47,805	4.920
2006	31,442		59,501		46,575	
2007	30,540		59,771		44,932	
2008	29,053		57,392		45,448	
2009	24,389	0.071	55,393	0.020	44,053	4.469
2010	26,109	0.070	54,636	0.019	48,572	4.433
2011	24,344	0.067	54,524	0.019	38,862	4.117
2012	23,674	0.069	53,769	0.019	43,720	4.190
2013	24,231	0.071	53,418	0.018	43,794	

Source: DECC (2014b); Enerdata (2015).

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